DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT D-77-17

FEASIBILITY STUDY OF GENERAL CRUST MANAGEMENT AS A TECHNIQUE FOR INCREASING CAPACITY OF DREDGED MATERIAL CONTAINMENT AREAS

by

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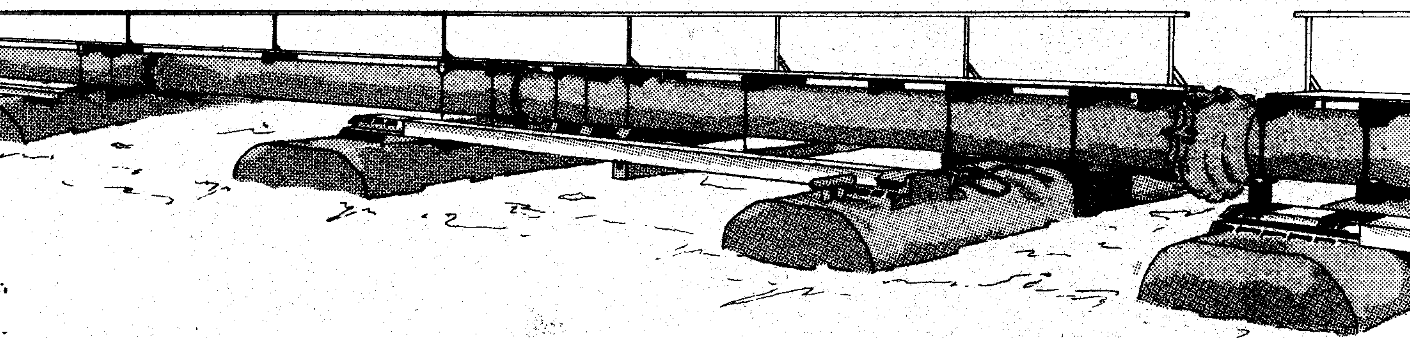

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SUBJECT: Transmittal of Technical Report D-77-17

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1. The report transmitted herewith represents the results of a study conducted as part of Task 5A (Dredged Material Densification) of the Corps of Engineers' Dredged Material Research Program (DMRP). This task is part of the Disposal Operations Project of the DMRP and is concerned with developing and/or testing promising techniques for dewatering or densifying (i.e., reducing the volume of) dredged material using physical, biological, and/or chemical techniques prior to, during, and/or after placement in containment areas.

2. The rapidly escalating requirements for land for the confinement of dredged material, often in urbanized areas where land values are high, dictated that significant priority within the DMRP be given to research aimed at extending the useful life of existing or proposed containment areas. While increased life expectancy can be achieved to some extent by improved site design and operation and to a greater extent by removing dredged material for use elsewhere, the attractive approach being considered under Task 5A is to densify the in-place dredged material. Densification of the material would not only increase site capacity but also would result in an area more attractive for various subsequent uses because of improved engineering properties of the material.

3. In most disposal areas containing fine-grained dredged material, a relatively thin desiccation crust tends to form with time. Crust material is dense, and the engineering characteristics are better than that of the underlying wet material. As part of Task 5A, methods are being evaluated to take maximum advantage of this crust and to promote its formation through various means. Little information is available on crust formation within containment areas. If crust management is to be used, information such as rate of crust formation must be known. The objective of this study (Work Unit 5A06) was to determine the influence of meteorological conditions and the physical, chemical, and mineralogical properties of fine-grained dredged material on the formation of crust resulting from evaporative drying. Also methods of managing a containment area to maximize crust formation were evaluated. The study was conducted by the Texas A&M Research Foundation, Texas A&M University.

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4. Fine-grained dredged material was obtained from four sites and the physical, chemical, and mineralogical properties of the materials were determined. Evaporation tests were conducted in the open and in an environmental chamber. In these tests, the influence of temperature, solar radiation, wind speed, humidity, rainfall, soil type, and water table elevation on crust formation was evaluated. Methods of managing the containment area to maximize crust formation were investigated.

5. After decantation, the water content of the surface layer of the materials evaluated was equivalent to about 2.5 times the liquid limit. Evaporation during the first stage of drying was nearly the same as that from an open pan of water until the water content decreased to about 1.8 times the liquid limit. After this, drying proceeded at a rate dependent on the transport of moisture to the surface.

6. As fine-grained material in a containment area desiccates, a crust forms and surface cracks open. The volume shrinkage is equivalent to the volume of water evaporated as the crust forms, and evidence is given that the volume change is irreversible. Rainfall is shed from the crust and drains into the desiccation cracks, from which it can run off if channels are provided to the outflow weir.

7. Management practices investigated during the study included stirring and the frequent removal of thin layers of crust. These procedures produced only small short-term increases in the evaporation rate. Systems were developed to form surface drainageways and to remove thicker layers of desiccated crust.

8. The relationships developed through this study will be used to develop guidance for the management of containment areas to maximize their capacity through dewatering. The management guidelines will present techniques for dewatering and the rates at which densification will occur. These guidelines will be the final product of Task 5A.

JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

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The influence of meteorological conditions and the physical, chemical, and mineralogical properties of fine-grained dredged material on the formation of crusts resulting from evaporative drying in confinement areas was evaluated. After decantation, the moisture content of the surface layer is equivalent to about 2.5 times the liquid limit. Evaporation of moisture during the first stage of drying is nearly the same as that from an open pan until the moisture

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content decreases to about 1.8 times the liquid limit. After this, drying proceeds at a rate dependent on the transport of moisture to the surface. As the material desiccates, surface cracks open. The volume shrinkage is equivalent to the volume of water evaporated as the crust forms, and evidence is given that the volume change is irreversible. Rainfall is shed from the crust and drains into the cracks, from which it can run off if channels are provided to the outflow weir. Management practices, including stirring and the removal of a thin layer of crust, produced only small increases in evaporation rate for a few days. Systems were developed to dig drainage trenches in the confinements and to remove the consolidated crust. A small dredge appears to offer the most promise for cutting deep or wide surface drainage ditches.

CONTENTS

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PREFACE

This report presents the findings of a study conducted to determine the feasibility of crust management as a technique for increasing storage capacity of dredged material containment areas.

The study was conducted by the Texas Engineering Experiment Station and the Texas Agricultural Experiment Station under Contract No. DACW39-75-C-0120 to the Environmental Effects Laboratory (EEL), Waterways Experiment Station (WES), Vicksburg, Mississippi. Administrative assistance was provided by the Texas A&M Research Foundation. The study forms a part of Task 5A (Dredged Material Densification) of the Dredged Material Research Program (DMRP) Disposal Operations Project (DOP).

The report was written by Dr. K. W. Brown, Soil and Crop Sciences Department, Texas Agricultural Experiment Station, and Dr. L. J. Thompson, Civil Engineering Department, Texas Engineering Experiment Station. Technical assistance was provided by Drs. Don DeMichele, Industrial Engineering, and R. Tanenbaum, Civil Engineering. Messrs. J. C. Thomas, K. Launius, S. G. Jones, J. B. Allison, M. D. Gerst, and S. Smith also assisted.

Contract manager for EEL was Raymond L. Montgomery, Chief, Design and Concept Development Branch. The study was under the supervision of Dr. T. Allan Haliburton, Manager, Task 5A, Mr. Charles C. Calhoun, Jr., Manager, DOP, and the general supervision of Dr. John Harrison, Chief, EEL.

Directors of WES during the conduct of the study and preparation of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

FEASIBILITY STUDY OF GENERAL CRUST MANAGEMENT AS A TECHNIQUE FOR INCREASING CAPACITY OF DREDGED MATERIAL CONTAINMENT AREAS

PART I: INTRODUCTION

Background

1. Large volumns of sediment must be dredged annually to maintain the navigational channels in the United States. In recent years, there has been an increase in the amount of dredged material placed in confined land disposal areas primarily because of environmental constraints that have greatly restricted disposal of dredged material in open water. Under current management practices, retaining dikes are constructed and dredged materials are pumped into the confinement in one or more lifts which may be as thick as 2 to 3 m during one pumping. The fine-grained dredge material flows across the confinement area and generally represents a large fraction of the total material deposited. Supernatant water is then released through sluice structures or weirs. In many instances, no steps are taken to enhance drainage from the confinement area, and the fine-grained dredged material remains at high moisture content and low unit weight for years after placement. The resulting storage of large volumes of water effectively reduces the capacity of disposal areas.

2. Therefore, applicable techniques and alternatives for managing the dewatering and densifying of the materials must be developed so that the service life of active disposal sites can be increased and so that sites which have been filled might be rejuvenated.

3. In areas where the slurry is exposed, a surface crust is formed as the water evaporates. While evaporative forces work to densify the upper portion of the slurry, the crust may hinder the evaporation of water from lower layers in the deposit. Field observations

have indicated thick masses of fine-grained dredged material at high moisture contents and low unit weight under these crusts. Little information is reported about the rate of development of such crusts or the thickness they attain, and their influence on evaporation rates.

Purpose

4. The purpose of this study was to investigate the factors influencing the formation of desiccation crusts on fine-grained dredged materials, to develop methodology to predict the rate of crust formation, to evaluate the influence of its removal, and to suggest management which would optimize densification. Specific objectives were to:

- a. Inventory and review existing information on the factors influencing the formation of crusts.
- b. Develop methodology to investigate and predict the influence of environmental conditions on the rate of crust development, the effect of crust removal, and optimum time of crust removal to maximize densification.
- c. Make recommendations that might be implemented to manage the crust, including operational requirements, equipment, and possible costs.

Scope

5. Past reports on the management of dredged material confinement areas directed toward densification were reviewed, as was the pertinent information on the properties of fine-grained, shrinking-swelling soils, and factors influencing water loss by evaporation from bare soils.

6. Bulk dredged material samples were collected from confinement areas at four selected locations. These were near Philadelphia, Pennsylvania; at Toledo, Ohio; near Norfolk, Virginia; and at Mobile, Alabama. These materials were thoroughly characterized and utilized in evaporation studies throughout this work. Results of these studies were used to evaluate the influence of selected management practices on water loss and material consolidation. Laboratory data collected

were used to extrapolate these results to other climatic regions and management practices, thus providing a tool for determining what might be expected.

7. Decantation of excess surface water resulting from dredging or rainfall is of primary importance since drying of dredged material can not occur if water is ponded on the surface. Three types of water removal were considered in this study:

- a. Decantation of surface water through a system of trenches in the material.
- b. Evaporation of water from decanted material, which appears to be the most economical method of volume reduction. The influence of environment and management practices on evaporation losses were also considered, and the influence of subsurface on densification.

Optimum management may include utilizing all three of these means of water removal. Their individual and combined influence on crust formation, water loss, and consolidation were considered in detail. Available equipment for digging drainage trenches in confinement areas was investigated by on-site observations and review of technical bulletins.

8. The anticipated decrease of evaporation, due to low conductivity of dried surface material, would necessitate crust removal if evaporative losses and consolidation were to continue. This could not normally be achieved with conventional equipment; therefore, a survey was conducted of low-bearing-pressure equipment and systems to remove the crust. This was accomplished by on-site observation and, in some cases, gathering information from brochures and literature.

Available Information

Dredged material densification

9. Several recent reports are available on the management of dredged material to enhance densification. A study by Dames and Moore, authored by Garbe et al. (1975), reported that stirring a 114-cm-thick layer of dredged material with a bulldozer greatly increased the rate of evaporation and subsequent densification. They, in fact, claim

evaporation rates as great as 30 cm of water in 20 days. These rates far exceeded potential evaporation for the period of measurements, indicating that moisture was lost not only to evaporation but also by some other pathway. The 1975 study stated that the base of the confinement area was permeable and that the substratum became mixed with material being manipulated. It is possible that much of the phenomenal loss of water attributed to evaporation was actually lost through percolation.

10. Harding-Lawson Associates (1975) conducted both laboratory and field studies of dredged material drying rates as influenced by shallow and deep stirring. Laboratory tests were conducted under poorly controlled conditions. Although fans were used, no radiant energy was provided. Containers were lined with loose plastic which, from pictures, appeared to adhere to the sides of the shrinking material eliminating evaporation from natural shrinkage cracks. They concluded that stirring disrupted the dry surface layer and enhanced evaporation. While this assertion may be valid, neither the magnitude of the effect nor its validity in the field can be properly judged from these tests.

11. In the field studies of Harding-Lawson Associates (1975) the initial moisture contents of the materials were highly variable; losses of water may have been by drainage as well as evaporation. Unfortunately, their unreplicated tests on one material do not support their conclusion that mixing made any difference in the drying rate.

12. To further investigate the influence of mixing on evaporative loss from dredged material, a study was undertaken by Durham (1976). He exposed two large bins of simulated dredged material to the atmosphere. The top 7.5 cm of one was mixed daily; the other was not disturbed. Material in both containers lost essentially identical amounts of water, and losses did not exceed potential evaporation rates. His study was conducted under carefully controlled conditions and effectively contradicts the conclusions of the previous studies.

13. Harding-Lawson Associates (1974) reported limited success with sand drying beds to dewater dredged material. They found that

fine-grained materials soon plugged the pores thereby decreasing drainage markedly. The same problems may occur with drainage through sand ditches or sand-filled drainage channels within the confinement area. Pore clogging may not, however, inhibit their use in removing surface water if cracks form to the drains.

14. The influence of other management practices, including providing surface and subsurface drainage and crust removal or incorporation, has not been investigated, nor is it known how a dried crust will respond when another layer of material is placed on top of it.

Physical properties

15. Several studies have reported on the physical properties of dredged material. Krizek and Salem (1974) investigated the properties of dredged material in several confinement areas at Toledo, Ohio. They found that both the clay and silt contents increased from essentially none at the inflow pipe to about 40 percent of each at the outflow weir. Properties of the dredged material on the four sites investigated were essentially the same, thus allowing the development of one set of relationships. A coefficient of permeability from 10^{-4} to 10^{-9} cm sec^{-1} as the void ratio decreased from approximately 10 to 1 was reported. The average unit weight increased about 4 percent per year and average shear strength about 3.5 kN/m^2 per year during the first five years. They suggested that the rates of change of these parameters will decrease with time unless management practices are initiated to accelerate dewatering.

16. Krone (1973) investigated the degree of aggregation of dredged material particles. He found that addition of only small amounts of saline water caused aggregation and rapid sedimentation. The rate at which clear water accumulated above settling dredged material depended not only on grain size, as indicated by Stoke's law, but also on salt content of the water, percent solids in the slurry, and slurry depth. In addition, wind may cause turbulence which could resuspend a fraction of the fine particles.

Mineralogy

17. Krizek et al. (1973) and (1974) have reported that the samples they analyzed from Toledo contained significant fractions of illite and kaolinite; however, they reported only qualitative results.

Organic matter

18. Krizek and Salem (1974) found 2 to 4 percent organic carbon in samples of dredged material. They suggested that some of the organic carbon content of samples collected from confinement areas may be attributed to vegetation which was burned during the filling operation. They also reported, however, that the samples which had greatest carbon content had an oily odor.

Shrinking and swelling

19. No reports could be found documenting the shrinking-swelling properties of dredged material; however, many reports of the shrinking-swelling properties of fine-grained soils in a disturbed state and in their natural state are available. These reports may provide some insight into the behavior of such materials after disposal in confined disposal areas.

20. The change in soil material volume as moisture content changes is influenced greatly by the amount and kind of clay present. When materials containing certain clay minerals are dried, shrinkage and cracking will occur. When soils are rewetted, they swell as moisture is absorbed. In soils and most natural deposits of clay, volume changes occur equally in all three dimensions.

21. A soil with a large fraction of smectite clay exhibits large cracks in the horizontal dimension on drying. Measurements against a deep benchmark reveal that shrinkage also occurs in the vertical dimension. Elevation changes as great as 8 cm have been reported in the field (Aitchison and Holmes, 1953). Soils are rarely uniform in the vertical or horizontal dimension nor is water distribution uniform within them.

22. Swelling of soils has been correlated with other selected properties. Russell (1954) noted that swelling is proportional to the

cation exchange capacity (CEC) of clay soils. A correlation between soil shrinkage, CEC, and specific surface was reported by Gill and Reaves (1957). Other factors including kind of exchangeable cations, content of organic matter, and content of iron are important (Davidson and Page, 1956). Overburden pressure and degree of compaction may also influence the change in volume with a change in moisture content.

23. Shrinkage cracks that form in soils in situ will be widest near the surface and may extend to depths of several metres. Woodruff (1936) demonstrated that as a clay soil dried, the change in the vertical dimension decreased with depth. Except for depths very near the surface, in situ soils do not reach soil moisture suctions of more than 15 bars. Clay soils dried to this suction still retain sufficient water to cover all soil particle surfaces with several molecular layers of water. Further drying by artificial means such as oven drying results in additional decreases in volume which are never experienced in the field.

24. The first increments of moisture removed from saturated soil materials during drying come from the large pores between the aggregates. Very little volume change results from such removal. Reduction in volume for most soil materials is then nearly linear over a wide moisture content range. In the intermediate range, moisture is removed from between particles, and the volume change is typically proportional to and nearly equal to the volume of moisture lost. At low moisture contents, volume loss is again much less than moisture loss. At these moisture contents, repulsion between particles limits further collapse. Soils containing clays with less surface area will exhibit less volume change upon drying. Soil material containing very little clay will exhibit little or no change in volume as moisture is removed.

25. The majority of data available on volume changes of soils as a function of moisture content has been collected on samples as they shrank. By maintaining a slow moisture loss rate, the moisture content of a sample can be controlled to be nearly uniform throughout. Unsaturated hydraulic conductivity of fine-textured soils is low, and it is thus difficult to establish uniform moisture contents as a sample is

rewetted. By taking special precautions, however, Haines (1923), and Chang and Warkentin (1968) demonstrated that the dependence of volume on moisture content is hysteretic. Rewetted samples occupied less volume at a particular moisture content during rewetting than they did during drying. Chang and Warkentin (1968) also reported that both the volume occupied by a given weight of soil and the hysteretic effect were less for compacted samples.

26. Several forces are involved in determining volume changes as soils dry. As moisture is lost, pressure differences develop across air-water interfaces which occur where water bridges the particles. As moisture is removed from the system, moisture will be drawn by pressure gradients from other locations to help minimize pressure differences. As moisture is withdrawn, the air-water interface becomes more concave drawing soil particles closer together. Moisture is held between the particles by matric forces resulting from adhesion of water to particle surfaces, cohesion between adjacent water molecules, and osmotic forces resulting from attraction of ions for water. As moisture is withdrawn from between the particles to satisfy atmospheric demand, the particles will move closer together until repulsion prevents further collapse.

27. The species of ions present on the exchange sites influence the amount of shrinking and swelling exhibited by a soil. Sodium-saturated montmorillonite, illite, and kaolinite swelled more than when the same clays were saturated with calcium (Mielenz and King, 1955). The greater swelling associated with monovalent ions is a result of greater expansion of the diffuse double layer between adjacent particles. The presence of other materials, including iron hydroxides, stabilizes the clay and prevents nearly all volume change.

Evaporation from soil surfaces

28. Although few papers have been written on moisture evaporation from dredged material sites, many have been written on evaporative loss of moisture from soils. These will be briefly reviewed to elucidate present understanding of the factors involved and methods of applying

them. Loss of moisture from the bare soil surface has been generally viewed as a two-step process. During the first stage, conductivity from moisture reserved in the soil is great enough to supply more than can be lost into the environment. During this phase, loss is thus controlled by the prevailing environment including amount of net radiation available at the surface, windspeed, air temperature, and vapor pressure. During the second stage of drying, soil conductivity is too low to supply the evaporative demand, so evaporation becomes independent of the environment as long as the atmospheric demand is greater than the rate of supply. These two phases generally follow each other as the soil dries, but as a result of the diurnal climate pattern and the variation in climate from day to day, the system may shift back and forth between the first and second stage of drying. For example, rewetting overnight may cause the environment to control moisture loss during the morning, while atmospheric demand may be too great during the afternoon and the environment may no longer play a role. Similar reversing to the first stage, after the second stage has begun, may also occur during periods of very low evaporative demand (i.e. on cloudy, humid days). Gardner and Hillel (1962) report, however, that temporary interruption of the evaporative process had little effect on cumulative water loss.

29. Within the soil, moisture moves because of suction gradients resulting from either gravity, matric suction, osmotic suctions, and to a lesser extent, pressure differences. Temperature gradients can also be important in causing moisture movement. Water will move from regions of warm temperature to regions of cooler temperatures both in the liquid and vapor phases. Detailed discussions of these processes are available in a variety of texts including Rose (1968 a & b) and Baver et al. (1972). Philip and DeVries (1957) considered the details of temperature on the influence of thermal regions on water flux. Thermal effects contribute to moisture flux in soils of medium moisture content. They had little effect on moisture movement in wet or dry soils. The influence of crusting on the evaporation rate has been investigated by several researchers. Bresler and Kemper (1970) reported that rainfall-induced

crust retarded evaporation from the surface.

30. Gardner and Hillel (1962) worked on salt crust as an inhibition to evaporation. They reported that the formation of a salt crust on the soil surface greatly reduced evaporation. They also found that the removal of this salt layer restores the original E rate. Willis and Bond (1971) found that where a dry layer of soil was retained on the surface, the evaporating rate was greatly reduced.

31. Loss of moisture from cracks in shrinking-swelling soils has been studied by Ritchie and Adams (1974). They investigated a drying soil enclosed in a lysimeter. Although moisture losses were low, 81 percent of that loss occurred through the cracks. When they covered the entire surface except the cracks, 0.77 cm of moisture was lost per day over the crack area. During the period of their investigation the potential evaporation averaged 0.37 cm/day. Thus, the cracks were conducting moisture to the surface in the form of vapor rapidly enough to supply about twice the demand per unit area. Several computerized models of evaporation from bare soil surfaces have been developed (van Bavel, 1966 and Hillel, 1975). None of these, however, take into account moisture loss from the cracks.

32. The presence of a water table below the surface may provide a large enough moisture supply to continuously rewet the surface so that the evaporation process may never enter the second stage. This possibility has been investigated by Gardner and Fireman (1958) and later by Ripple et al. (1972). They reported that if the saturated conductivity is great enough for the material being considered, as it is for natural soils, and if water tables are within 100 cm of the surface, evaporation will continue at potential rates even under conditions of the highest expected evaporative demands. With lower evaporative demands, moisture will continue to be lost at the potential rate even when the water table is deeper.

Evaporation and precipitation data

33. The most consistent set of data on evaporation across the continental United States is the pan evaporation data collected by the

National Oceanic and Atmospheric Administration (NOAA) in cooperation with State and Federal agencies. Daily data are available for approximately 400 stations. These data have been tabulated in the U. S. Weather Bureau (1965) "Climatic Summary of the U. S. - Supplement for 1951 through 1960." Unfortunately, the records are not all of the same length and do not all include data for each month of the year. No published maps of the data were available. Therefore, this study undertook to develop monthly maps of pan evaporation for the continental U. S. based on the data taken between 1931 and 1960 with typical station record lengths of 13 years (Figures 1-12). The evaporation patterns in the Rocky Mountains are probably more complex than shown in the figures, but more detailed data was not available. It is suggested that these monthly maps might serve as an estimate of the amount of moisture that could evaporate from a wet soil surface at a particular location.

34. There are several reasons why evaporation of water from a standard class A pan may not be representative of moisture evaporation from a wet, bare soil. Even if pan exposure is ideal, i.e., surrounded by a well-watered, freely evaporating surface, the temperature regime of the water surface will differ from that of a wet soil. This results because the pan is supported above ground, and the water temperature is not dampened by heat transfer to and from the soil below. Secondly, thermal inversions may occur in the water in the pan. These, coupled with greater mixing due to the influence of wind at the water surface, may cause the temperature to be greater or lower than that of the soil, resulting in greater or lower evaporation from the pan.

35. Exposure is also often a problem with pans. Ideally they should be located in a large flat field surrounded by a freely evaporating surface with no obstructions to wind and radiation. In reality, however, many pans are exposed near runways, parking lots, or buildings. This often results in extra heat being transferred to the air passing over the pan causing a greater evaporation rate than would otherwise occur.

36. Some of the influences of these difficulties would offset

each other over a period of time; however, others may be cumulative. Nonetheless, pan evaporation data are the most consistent set of pertinent data collected over the continental U. S. and were thus selected to be used for the purpose at hand. Other techniques would require the use of climatic data and assumptions about the relationships between windspeed, heat, and water vapor transport in the air above the evaporating surface. For the present, it is suggested that results of these calculations would be too complex and offer little improvement.

37. Mean precipitation maps for each month for the continental U. S. are published in the "Climatic Atlas of the U. S. (1968)" and are not repeated here.

38. If surface drainage is not provided to conduct rainwater off confined dredged material, the rainfall will have to evaporate before the drying process will proceed. Thus, if drainage is not provided, evaporative loss will be reduced from the potential (in this case pan evaporation) by the amount of rainfall. Therefore, monthly maps of net evaporation were prepared (Figures 13 through 24) that indicate the greatest possible water loss from dredged material if no rainwater is allowed to drain.

39. Actual evaporation from wet dredged material is probably bounded by the values of gross and net evaporation given in the two sets of maps. Even with the best management, runoff from small rains will be retained and some of the water from large rains will be absorbed before it can run off. It is not, however, anticipated that evaporation from a wet soil surface will exceed pan evaporation by more than 10 or 15 percent at any one time and, on the average, would approximate it more closely.

40. Vegetation normally takes over some dredged material sites, particularly those which contain freshwater dredged material. The presence of vegetation is expected to have little influence on moisture loss to the atmosphere during the early stages of evaporation when the dredged material surface is wet. In later stages, when the surface dries, the roots of the vegetation will be much more effective in transporting water to the surface than will result from the unsaturated con-

ductivity of the soil. Therefore, as long as the material does not dry beyond a suction of about 15 bars, plant transpiration would be expected to approximate pan evaporation.

41. Vegetation may, on the other hand, have adverse effects in that it may impede free surface drainage, resulting in more absorption of moisture by partially dried material. This disadvantage would be offset in the later drying stage, particularly if proper surface drainage is provided.

PART II: COLLECTION AND CHARACTERIZATION OF SAMPLES

Field Sample Collection

42. Bulk samples were collected from one location within each site; details of the sites, a description of the origin of the dredged material, and related observations are given in Appendix A. Sampling locations were selected to provide samples from a freshwater site (Toledo), a saltwater site (Norfolk), and two sites which have a possibility of mixture of salt and freshwater in the channels being dredged (Philadelphia and Mobile). Sampling locations also represent climatic variations and differences in geological formations from which the dredged material originated.

43. Sample locations within the dredged material confinement areas were selected such that coarse particles had been removed by sedimentation and the materials consisted mainly of fine-textured, black deposits. Samples were collected below the crusts found in the field and were placed in three barrels at each site and shipped to College Station, Texas, via motor freight.

44. Water samples from the water table were collected at each location. In addition, at some locations, samples of dredged material were taken at several depths for moisture content determinations. All samples were collected in August and September of 1975.

Physical and Chemical Properties

45. Samples from each of the three barrels of material collected from each sampling location were taken by removing cores from the center of each barrel. Laboratory analyses including moisture content, particle-size distribution, volatile solids, total organic carbon, pH, and particle density were determined on these samples and average values will be presented.

46. Particle-size distribution was determined by the hydrometer

method described by Day (1965). The pH determinations were made on a 1:1 soil:water suspension. Particle density was determined on three samples of material from each location. A water displacement technique described by Blake (1965a) was utilized.

47. Particle-size distribution of the four dredged material samples is shown in Figure 25. No sand >2 mm was found in any of the samples. The Philadelphia sample had a greater fraction above 0.1 mm than did the other three samples. The Mobile sample contained a high fraction of very fine clay followed by the Toledo sample with about half as much clay. Philadelphia and Norfolk samples had very similar particle-size distributions. Texturally, all samples would be classified for agricultural purposes as silt loams, except for the sample from Mobile, which was a clay. Classifications in the Unified Soil Classification System will be discussed later.

48. Total volatile solids are shown in Table 1 as are several other properties. The Mobile and Toledo samples lost the greatest weight on ignition, while the Norfolk and Philadelphia samples lost less. Loss by ignition includes both organic matter and mineral matter, especially carbonates, which may vaporize at temperatures less than 800° C. All samples appeared black, but total organic carbon content ranged from only 1.3 percent for the Norfolk sample to 2.7 percent for the Mobile sample. These values are within the range reported for agricultural soils. The Toledo and Norfolk samples effervesced when treated with hydrochloric acid (HCl), indicating the presence of carbonates. The Mobile sample gave off some bubbles, while the Philadelphia sample did not effervesce, indicating little or no free carbonates, respectively. Volatile solids correlated well with the presence of carbonates and/or an organic fraction, suggesting that these may have been major constituents lost on ignition. The pH values of all samples were neutral (7.0) to very slightly basic (7.3). Electrical conductivity of the samples from the water table at sampling locations is also given in Table 1 as is sodium concentration. Water collected at the Norfolk and Mobile locations had conductivities and sodium contents

which differ only slightly from seawater. The water samples from Toledo and Philadelphia were nearly free of salts indicating that the materials were dredged from fresh water.

Mineralogical Analysis

49. Mineralogies and percent composition of the clay fraction from the four dredged material samples were determined by X-ray diffraction. Soluble salts, carbonates, organic matter, and free iron oxides interfere with fractionation of clay from soil, and orientation of clay particles may even cause scattering of the X-rays resulting in poor X-ray diffraction patterns. Soluble salts were removed by washing 25-g samples with distilled deionized water until conductivity readings were nil. Carbonates were destroyed by adjusting the pH of the sediments to pH 3.5 with HCl. The pH was maintained at 3.5 with continual additions of acid until effervescence ceased. The samples were washed with water and adjusted to pH 5 with sodium acetate for removal of organic matter. Organic matter was destroyed with 30 percent H_2O_2 employing the procedure reported by Jackson (1956). Free iron oxides were removed by the procedure reported by Mehra and Jackson (1960) which employs a dithionite-citrate solution. Samples were treated twice prior to being dispersed in pH 10 water. Particles were allowed to settle 8 hr, following which the clay suspension was siphoned off into 250-ml centrifuge tubes for K and Mg saturation. Duplicate suspensions containing at least 0.1 g of clay were transferred to 100-ml centrifuge tubes and washed with 1.0 $\underline{N}$ KCl and 1.0 $\underline{N}$ $MgCl_2$. Clays were washed free of excess salt. The Mg-saturated samples were mounted on glass slides, whereas K-saturated samples were mounted on vicor slides so that they could be heated.

50. The K-saturated sample was irradiated after drying. It was then heat treated for 6 hr at $300^{\circ}C$ and irradiated again. This was followed by a 6-hr heat treatment at $550^{\circ}C$ and irradiation once more.

Magnesium-saturated samples were air dried and saturated with ethylene glycol vapors by placing the sample in a vacuum desiccator containing a free surface of ethylene glycol.

51. Amounts of clay minerals were calculated from Bradley's formula employing mica as the reference mineral. Quartz and feldspar were estimated from the percent of chart deflection. Results of the mineralogical analysis are shown in Table 2. Methods employed were selected to remove interferences and thereby enhance qualification and quantification of the soil clay minerals. The sharpness of the peaks obtained on X-ray diffraction patterns was indicative of highly crystalline material, which aided in mineral identification. The <2 μm fraction of the various samples contained a full range of minerals, but generally was predominated by two or three. One would expect the predominate minerals to exert the greatest influence with respect to physical properties of dredged sediments. Clay fractions were comprised largely of mica and kaolinite, which are noted for their low cation exchange capacity (CEC) and surface area, and low shrink-swell properties. The sample from Mobile contained the largest amount of smectite, which should make it more prone to shrink and swell.

Engineering Properties

52. In order to better classify and predict behavior of dredged material, Atterberg limit, vane shear, permeability, and shear-viscometer tests were performed. Standard procedures for conducting these tests were employed (Lambe 1951), with the exception of the shear-viscometer, which was developed by Carpenter et al. (1972). The experimental results are presented in Tables 3 and 4.

Atterberg limits

53. When these materials were tested by adjusting their moisture content without initial drying and grinding, they were classified as highly plastic silts (MH) except for the Mobile sample which was an inorganic clay of high plasticity (CH). When the same materials were

dried, rewetted, and retested, the results showed reduced Atterberg limits that resulted in a change in classification (Table 4). After drying, the Philadelphia and Toledo samples were classified as inorganic silts (ML), the Norfolk sample was an inorganic clay (CL), and the Mobile sample was an organic clay (OH). The results indicated that once dried, none of the materials readily reabsorb moisture.

54. The liquid limit and plasticity index were much larger for the Mobile sample than for the materials from the other three locations. The greater values were associated with finer texture and a greater fraction of shrinking-swelling smectite clay in the sample.

Shear strength

55. Shear strength was obtained using both the vane shear test and the shear-viscometer.

56. Vane shear strengths were obtained at the moisture contents of the samples as collected in the field and at moisture contents in excess of and less than the natural moisture content. Both fresh and salt water (4 g of sea salt per litre of water) were used to adjust the moisture content. As expected, the shear strength increased with a decrease in moisture content. Saltwater tests were not conducted for the materials from Philadelphia and Toledo since they originated from freshwater dredging.

57. The addition of fresh water to the Mobile samples caused the shear strength to increase rather than decrease. It is speculated that this resulted from mass cation exchange. Results show that, even at a low moisture content, all materials were soft and would be incapable of supporting loads in excess of a few hundred kilograms per square metre.

58. In essence, the shear-viscometer measures shear strength of a soil as a function of strain rate. A diagram of the device is presented in Figure 26. Shear resistance of the material was measured by a load cell in an Instrom Universal Testing Machine. Shear displacement speeds of .5, 5.1, and 51 cm/min were used.

59. Freshwater tests for the Toledo and Philadelphia materials were as expected: specifically, an increase in shear strength with in-

creasing strain rates. Freshwater tests on the remaining materials produced conflicting results as these materials originated in salt water. Thus, saltwater tests were conducted producing the expected results (Figure 27). In general, viscosity of the material at high moisture contents decreases with increasing strain rates. Similarly, with the change in moisture content effect on shear strengths obtained from the vane shear tests, shear strengths obtained within the range of strain rates applied are still low.

Permeability

60. Variable-head permeability tests were conducted on all four samples. Results ranged from $5.86 \cdot 10^{-7}$ to $4.08 \cdot 10^{-6}$ cm/sec, which are within the limits expected for a plastic silt. Thus, natural drainage of all the materials is poor.

61. A consolidometer-permeameter was used to test samples to pressures of 200 bars. All the consolidation loads were measured directly using dead weights and lever systems. Flow rates were measured in graduates at atmospheric pressure and room temperature. The samples used were 11.5 cm in diameter and 4 to 5 cm long. Starting with a saturated slurry, a load was applied by the lever system and water was pressed out of the sample. The load was left on long enough for the porosity to become constant. Sea water was then forced through the sample by another lever system until the flow rate reached a constant. This process was repeated by increasing the load on the main lever system until 200 bars was reached.

Moisture Content-Unit Weight-Suction Relationship

62. Bulk samples of each material were taken for use in determining moisture-unit weight relationships. The bulk samples were wetted using water of the same electrical conductivity as that collected from the respective field location; this was done by mixing the sample in surplus water. Three sets of water desorption data were collected on dredged material from each location. For the first test, the materials

were desorbed from their saturated moisture content to a range of potentials by using tension tables or pressure plates (Richards, 1965). The second set of desorption data was taken on samples which were rewetted but not reconstituted after being allowed to air dry from their initial moisture contents. The third set was taken on samples which had gone through two drying and rewetting cycles.

63. The unit weight was determined on samples which were too wet to handle by weighing a dish filled to a known volume. Measurements of volume on samples of lower moisture contents were made by the water-displacement techniques (Blake, 1965b). Paraffin was used in these tests to prevent moisture from entering the soil.

Permeability

64. Special containers with sloped walls were used to determine unsaturated conductivity of the dredged material as shown in Figures 28 and 29. Containers were 34 cm deep, 32 cm in diameter at the top, and 24.5 cm in diameter at the bottom; all were equipped with plastic liners. Dredged material was prepared and placed in the containers in the same manner as described for the other experiments. Three tensiometers were placed in the suspension at depths of 6, 15, and 22 cm by hanging a rod connected to each one over a support resting across the container top. After decantation was completed, the support was removed and the tensiometers were allowed to move as the material shrank. Sand was placed, as necessary, between the plastic liner and the container wall up to the level of the material to prevent evaporation from the gap that opened between the material and the side walls of the container. The sloped walls of the containers and lateral pressure resulting from the sand also helped prevent crack formations.

65. The tensiometers were connected to a container of manometer fluid, which had a density of 2 g cm^{-3}, to provide good resolution in the low suction ranges. When a tensiometer developed enough suction to draw the manometer fluid over the top of the tube, the manometer was

flushed and the tensiometer tube was placed in a mercury well for future readings. Measurements of the distance between the top of the container and the top of the rod attached to each tensiometer and of weight loss were taken daily.

66. Unsaturated conductivity was calculated from Darcy's Law used in the following form:

$$K = -q \frac{dz}{d\psi}$$

where: K = conductivity at a given potential, cm/day

q = flux of water, cm/day

z = the depth, cm

ψ = suction, cm of water

The depth between the tensiometers changed with time, necessitating use of an average depth over the time interval. The suction gradient was calculated over the depth interval between the time interval from the tensiometer readings. The suction associated with the calculated K was taken as the average over time and depth.

Isotropic Shrinkage Tests

67. There was no reason to suspect that shrinkage would be other than isotropic; nontheless, a simple test was conducted to find out. The materials were prepared by using a saturated paste that was placed in a dish of known volume and oven dried. The change in height of each sample upon drying was compared to the cube root of the change in volume. Height was measured directly and volume was calculated from initial and final diameter and height measurements. This was possible since all materials shrank uniformly and did not crack.

68. Height shrinkage and linear shrinkage calculated as the cube root of the volume shrinkage are shown in Table 5. The small differences which occurred are within the limits of the accuracy of measurements, confirming the assertion that shrinkage is isotropic. The Mobile samples showed the greatest loss of height and volume.

PART III: PROCEDURES FOR EVAPORATION EXPERIMENTS

Preparation of Dredged Material

69. In order to achieve the moisture content that existed immediately after original deposition, samples used in the evaporation studies were rewetted. This was done by mixing dredged material with excess water of an electrical conductivity similar to that of the water collected at respective sites. Mixing was achieved by means of a rotating beater driven by a gasline-powered posthole digger adapted to fit a barrel as shown in Figure 30. Mixing was continued until a homogeneous slurry was achieved.

70. The slurry was then transferred to the containers used in the experimental studies. These consisted of the bottom third of a 208-1 barrel fitted with a 12-cm hoop to extend the total height to 35 cm. The hoop was used to allow sufficient material to be placed in the container so that, after sedimentation and decantation occurred, the hoop could be removed and the container would be approximately full. Hoops were removed so that during the majority of tests a minimum of the drying material surface would be shaded by the container walls. In some cases, after several decantations, the material shrank well below the top of the container. In other cases, additional material mixed as described above was carefully poured on top of the first layer and decantation was repeated. Subsequent observations did not reveal discontinuities between the initial deposit and that added later.

Environment

71. A series of field studies were conducted between November 1975 and April 1976, at College Station, Texas. These studies provided a natural environment including diurnal changes of temperature, radiation, wind speed, and humidity. These parameters were recorded at an adjacent meteorology station and are given in Appendix B. In addition, a con-

tainer filled with water and of the same size as that used for the dredged material, without the hoop, was weighed daily to provide a measure of potential evaporation from a water surface.

72. Water loss from dredged material was determined daily by weighing. Shrinkage was also determined daily, or less frequently when changes were slow. This was done by measuring elevation difference between the dredged material surface and a stick laid across the top of the container. Measurements were repeatedly made at the same location in each container.

73. The area in which dredged material was exposed was protected from rainfall by an automatically activated rainshelter that allowed continuous evaporation studies without interference of natural rainfall. The shelter covered the containers when rain was detected and retracted automatically shortly after the rainfall ended (Figures 31 and 32).

74. A series of studies were conducted in an environmental chamber. Five containers, one filled with water, were placed in the chamber at any one time. Radiation, temperature, humidity, and wind speed were controlled. The conditions were set to simulate the high evaporative demands which occur on a clear hot day. Incident radiation over the dredged material samples was 0.44 $cal/cm^2/min$ during a 12-hr daylight period. During this period, the temperature was $32^{o}C$ and relative humidity was 25 percent. During the 12-hr night period, the temperature was $23^{o}C$ and relative humidity was 100 percent. Air flow through the chamber was a continuous 0.57 m/sec. For most studies, evaporation and shrinkage were measured in the growth chamber in the same manner as at the field station.

75. Decantation of all water was continued until no more could be removed. The hoops were removed from the containers and measurements of weight, shrinkage, and moisture content begun. Typical moisture contents at the beginning of the measurements were 180 percent. The containers were equipped with small rubber castors and set on platforms at elevations such that they could easily be rolled onto platform type scales with a resolution of about 200 g.

76. Sufficient fresh materials were available from each location for all the studies except the final one in which deeper containers were used. After each study, dried materials were broken up and stored underwater. The materials were prepared for the final study by further breaking up previously used materials and mixing them with water as described above. The mixing process required more time to complete than did the mixing of the original material. There were no indications that remixed materials behaved any differently from original materials.

Moisture Samples

77. Moisture samples were taken soon after decantation was completed by pushing a thin-walled tube into the material, inserting a stopper in the protruding end, and transferring the entrapped material to a moisture can. No hole was left in the material by this technique. Once the material became stiff enough, an open-faced soil probe 2 cm in diameter was used to collect samples. The resulting holes were sealed by inserting a polyvinyl chloride (PVC) tube into each hole, eliminating evaporation from the hole and preventing distortion of results in subsequent samples.

78. Samples taken at the end of a study were collected by sectioning dredged material with a large knife and removing samples at desired locations.

Evaporation Experiments

79. A series of experiments were conducted to determine the influence of environmental and crust management factors on rate of moisture loss and shrinkage of dredged material. For all the experiments, the materials were prepared as previously described. For clarity, the experiments will be described here and the designations will be used throughout the text.

Experiment A

80. Experiment A was a drying experiment conducted in the environmental chamber. One container of material from each location was used. Measurements were made of moisture loss by weight and of surface subsidence.

Experiment B

81. Experiment B was a drying experiment conducted in the field. Four containers from each location were prepared and allowed to dry simultaneously. The first container of each material was used to collect periodic samples at various depths to ascertain the moisture content profiles. Material in a second container was removed after a period of drying, broken up, replaced, and allowed to continue to dry. A thin crust was removed from the material in a third container after a period of drying. The fourth container was used in the rewetting studies to be described later.

Experiment C

82. Experiment C was designed to evaluate the influence of the water table depth on moisture loss and shrinkage rate. It was conducted in the environmental chamber using one container of each material (Figures 33 and 34). Before the materials were placed in the container, a 2-cm layer of pea gravel, followed by a 1-cm layer of sand, was placed in the bottom. A 2-cm-diameter standpipe was positioned along the inside edge of the container. It extended to the bottom and was perforated along the lower 2 cm. A 3-l bottle equipped with a bubble tube was fitted over the standpipe providing a supply of water to the gravel layer, thus maintaining a constant water table at the bottom of the dredged material. Two tensiometers were installed and read daily. After a period of maintaining a constant water table, the water supply was removed and the material was allowed to dry.

Experiment D

83. Experiment D was conducted in deeper containers to determine the influence of drainage and thickness of the layer upon drying. The containers were originally 95 cm deep with the same diameters as

before. Two containers of each of the four dredged materials were prepared, one with and one without an underdrain. The underdrain consisted of a 2-cm-thick gravel layer covered with a 1-cm-thick layer of fine sand and was connected to a bottle to collect the water which flowed out the bottom of the container. Containers were weighed daily, and the leachate was collected and measured as significant amounts accumulated. To prevent shading, the side walls of the container were cut down in stages with an oxy-acetylene torch. Cutting was done from the inside of the containers to prevent heating of the material.

Rainfall Simulation Study

84. To investigate the amount of rainwater absorbed by dredged material and the subsequent influence on evaporation and volume changes, dried samples of the material from each of the containers described above were exposed to 2.5 cm of rainfall at a rate of 2.5 cm/hr in an artificial rainfall simulator. The simulator generated rain with a drop-size distribution and impact energy similar to that of natural rainfall. The equipment used was similar to the one described by Morin et al. (1970). Weight and thickness of the sample section were determined before and after rainfall, and subsequent changes in evaporation rate were determined. To simulate good surface drainage, the rainfall that accumulated in the cracks was removed by a siphon soon after the rainfall.

Rewet Study

85. Selected containers of the materials which had dried to different moisture contents were flooded to 1 cm above the level of the crust with a measured amount of distilled water. The water was siphoned off periodically and measured to determine how much was absorbed by the material. After measurement, the water was carefully poured back into the material. Measurements of elevation with respect to the top of the container were also made periodically.

PART IV: RESULTS

Moisture Content-Unit Weight-Suction Data

Moisture retention

86. The moisture retention curves for dredged material as a function of suction are given in Figures 35 to 38. For all materials, less moisture was retained during the second and third drying cycles than during the first drying. Differences between the second and third dryings, however, were not discernible. The biggest decrease in moisture retention occurred in the Mobile material, which had the largest amount of clay and contained significant amounts of clay known for its shrinking-swelling properties.

87. The Mobile sample retained much more water at any suction than did the other three samples. At suctions of 1 cm of water, essentially saturated, the Mobile sample contained 190 percent water while the Philadelphia, Norfolk, and Toledo samples retained 138, 133, and 123 percent moisture respectively. At suctions of 1.5×10^4 cm of water, the Mobile material still contained 54 percent moisture while the others all retained 35 percent moisture. The dried and rewetted Mobile material still retained more moisture during the second drying than any of the other materials during the first drying.

88. The hysteresis is the amount of moisture retained after an initial drying and rewetting and is indicative of the formation of a soil structure containing more larger pores than were present in the original material. This characteristic will aid in dewatering in the field since when the material is rewetted it will drain more freely and not retain nearly as much water as it did during the first drying cycle.

Unit weights

89. The unit weights of the materials dried to different moisture contents are shown in Figures 39 to 42. For all cases, the second and third drying cycles reached given unit weights at lower and lower moisture contents, indicating that the structures achieved

during previous drying were resulting in large pores which held less water at the same unit weights. For all materials but that from Norfolk, the difference between the second and third drying was much less than between the first and second drying.

90. The Mobile material, which had the greatest clay content and greatest amount of shrink-swelling smectite clay, consistently contained more moisture at a given unit weight than did the other three materials for which the results were nearly identical. The Mobile material also still retained more moisture at given unit weights after the second and third drying than did the others.

Volume relationships

91. The relations between total volume expressed as a function of the volume of water in the dredged material during the first drying cycle are shown in Figures 43 to 46. The total volume of the material (V) is given in these figures as a fraction of maximum volume (V max) taken as that at saturation. Volume of water lost (Vw) is also expressed as a fraction of V max. A straight line representing one unit of total volume loss to one unit of water loss has been drawn through the data. For all of the samples, the line fell slightly below the wettest sample. This may be a result of the different procedure used to determine the volume of the wet sample. In any event, the discrepancies are of the order of anticipated experimental error. For most of the shrinkage, the data fell very close to the line, indicating that the total volume loss was equivalent to the volume of water lost. The Mobile sample underwent the biggest change in volume, with the dry material reaching 25 percent of the initial saturated volume. The other three materials behaved similarly and dried to an average volume equivalent to 38 percent of the original volume. The shrinkage curves break from a straight line for the Mobile sample when the volume reduces to 30 percent of the initial wet volume and for the other three materials when the volume reduces to about 45 percent of the initial volume. The different behavior of the Mobile sample from the other three materials is again attributed to the presence of the shrink-swelling clay in the Mobile sample.

92. The shrinkage curve breaks away from the straight line when the particles come into closer contact with each other. Shrinkage below this moisture content results in the voids filling with air. The second lowest data point on each curve is for the air dried sample. For all cases but the Philadelphia sample, the water loss between air dry and oven dry is large compared to the others.

93. For field purposes, the most valuable means of expressing the volume loss is as a function of the moisture content, which is the parameter most conveniently measured. This is done for each material in Figures 47, 48, 49, and 50 where the volume is again expressed as V over Vmax. Again, we have a straight line relationship over the majority of the range of moisture loss. These curves may be used in conjunction with field moisture content profiles to calculate how much volume reduction occurred between sampling times, or they may be used to determine the fraction of volume reduction which has been achieved and that which might yet take place if the material dries to some lower moisture content.

94. For comparison purposes, the lines only have been plotted together on Figure 51. The materials from Philadelphia, Toledo, and Norfolk all behaved essentially the same, while the curve for the Mobile material indicates greater volume reduction. The similarity of the three curves are associated with the similarities in liquid limit and plasticity index of the reconstituted samples. Overlaying the axes of the other data sets discussed thus far also reveals similarity in behavior related to the liquid limit and plasticity index.

95. The dependence of the volume reduction as a function of the suction is shown in Figure 52. Since the Mobile material retained more water at a given suction, it lost the same volume as the other samples at equal suctions. It is generally accepted that plant roots can only extract moisture which is held at suctions less than 15 bars. A thin surface layer of the crust may dry to suctions greater than the 15 bars volume, but even with plant root extraction, the lower limit of water

loss and total volume loss would be represented by the 15 bar values shown on these curves. For all the material tested, the minimum residual volume would be 42 percent of the original volume.

Permeability

96. The permeabilities of the Philadelphia, Toledo, and Mobile materials are plotted on Figures 53 through 55 as a function of suction, and in Figures 56 through 58 as a function of the moisture content. The permeabilities of the Philadelphia and Toledo samples are essentially identical, and about one-half an order of magnitude greater than that of the Mobile sample at all suctions. The relationships are conveniently represented by a straight line on log-log scale. The best fit equations of the lines are given on the figures. The Mobile material is, thus, less conductive at low suctions than the other materials. This may result in the first stage of drying being longer for the Philadelphia and Toledo materials. They may also dry to greater depths, and perhaps more uniformly, than the Mobile material.

97. Even when really saturated, the permeabilities of all materials were low and decreased rapidly as the suction increased. By suctions of 100 cm, the permeability of the Mobile material dropped to 0.001 cm/day. At the same suction, the permeability of the other two materials dropped to 0.005 cm/day. By suction of 1000 cm of water, the corresponding permeability decreased to 0.0001 and 0.0003 cm/day. Such low permeabilities indicate that water movement due to gravity alone in unsaturated material will be very slow. Movement caused by suction gradients resulting from evaporative water loss are expected to be much greater.

98. The moisture contents changed only over a narrow range despite the large range of suction encountered. Thus, the permeabilities as a function of moisture content are comparable only over a small range for the Philadelphia and Toledo samples. In the range from 58 to 64 percent moisture, the Toledo sample had permeabilities similar

to the Philadelphia sample. These permeabilities will be of value in calculating the water flux through the materials as they dry.

Consolidation test

99. From the total change of sample height in the consolidometer, the change in void ratio and change in porosity were computed. The log-log curve of the Norfolk sample is shown in Figure 59. The porosities were plotted on a log-log scale against consolidation pressures which showed the porosity as a function of vertical pressure in the process of progressive burial.

Permeability test results

100. The permeability tests were performed after each increment of consolidation test. The flow was plotted against time until a steady state of flow was achieved. The permeabilities were plotted against porosities on a log-log scale. The power law model was used to fit the test data. It was developed as follows:

$$k = Qn^{M} \quad M < 0 \text{ and } Q > 0 \tag{1}$$

where: k = coefficient of permeability

Q = the intercept of the line when the decimal porosity is one

M = the slope of the line

n = decimal porosity

Q and M are constants

The curve is shown in Figure 60. It is postulated that although these permeabilities have been determined on compressed samples, the results should be applicable to uncompressed samples of the same void ratios. Unfortunately, these tests were conducted on samples from Norfolk for which results were not available from the other test and comparisons are, thus, not possible.

Comparison of Field and Laboratory Moisture Content-Unit Weight Relationships

101. Samples of dredged material were collected for three of the four locations at a series of depths in each case. Measurements of unit weight and moisture content of these samples are plotted as special symbols in Figures 61, 62, and 63 for Philadelphia, Norfolk, and Mobile, respectively. Although only a few samples were taken at each location, the agreement between field data and the first drying curve obtained in the laboratory was good in all cases. This indicates that dredged material samples in each of the three locations had not previously dried much more than they were at the time they were sampled. It also shows that the laboratory procedures yield data which can be extrapolated to the field.

Comparison of Evaporation from 55-cm Pan and Class A Pan

102. Much of the evaporation data presented herein was compared to the evaporation data from a free-water surface in a 55-cm-diam pan in either the field or the environmental chamber. Since the standard Class A pan is 150 cm in diameter, it is of interest to compare the results, which could only be done in the field since the larger pan would not fit into the environmental chamber. The results of comparisons during Experiments B and D are shown in Figures 64 and 65. In one case, evaporation from the Class A pan slightly exceeded that from the 55-cm-diam pan, while the results were reversed in the other case. For all practical purposes, it is evident that differences between the two pans would be within the normal errors of experimental measurements.

Loss of Moisture and Shrinkage in the Environmental Chamber, Experiment A

103. The loss of moisture from the free-water surface and the dredged material in the environmental chambers is shown in Figure 66. The mean potential loss in the chambers was 0.665 cm/day or about double that found in the field. The chamber loss rate would be typical of hot and dry summer conditions.

104. After 6 days of drying, the loss of moisture from the Toledo and Mobile samples decreased below the potential. The other two samples continued at the potential rates until about the 12th day. Thereafter, all the loss rates decreased asymptotically toward zero. By the end of the period, the Philadelphia and Toledo materials had lost nearly the same amount of moisture followed by the Norfolk samples. By the 40th day of drying, the Philadelphia and Toledo samples had lost 66 percent of that lost by the free-water surface, while the Norfolk had lost 52 percent and the Mobile had lost 33 percent. The change in evaporation and the moisture loss after 40 days resulted from rainfall and will be discussed later.

105. The shrinkage curves for the materials are shown in Figure 67. Measurements had not begun until the 11th day, and the curves had already deviated from the linear losses evident in Experiment A. Materials were dissected at the end of Experiment A in the environmental chamber. The results are shown in Figures 68, 69, 70, 71, and 72. The samples had dried to lower moisture contents. The surface of the Philadelphia and Toledo samples had reached nearly their air dry moisture contents. This drying had penetrated 5 cm deep into the material. Even at these extremely low moisture contents, the influence of cracks on moisture content is not evident. The Norfolk sample had a very uniform moisture content; some indications of greater moisture content at the surface were still evident.

Loss of Moisture and Shrinkage of Materials in the Field, Experiment B

106. Loss of water from the open pan and the moisture loss from the containers of each of the four dredged materials' samples exposed in the field are shown in Figure 73. During the nearly 100 days that the containers were exposed in the field, the mean evaporative loss from the free water was 0.35 cm/day. Periods of higher and lower potential evaporation rate decreases are evident in the data. These variations may also, in some cases, be seen in the evaporation curves from the dredged material. Figure 74 shows containers of dredged material from two locations at various stages of drying.

107. During the first 8 days of the study, evaporation from all four samples equaled that from the free-water surface. During this time, moisture contents of the top 0- to 2-cm layers of the dredged material were 80, 62, 75, and 180 percent for the samples from Philadelphia, Toledo, Norfolk, and Mobile, respectively. Thereafter, each deviated from the potential curve with water lost at a rate which decreased with time so that by the end of the study samples had lost an average of 48 percent of the open-water evaporation. The rate of loss from all materials, except Mobile, was asymptotically approaching zero. The reason for the sudden upturn in moisture loss from the Mobile sample was unexplained.

108. The total loss of moisture from the four materials was ranked from greatest to lowest as follows: Toledo, Philadelphia, Norfolk, and Mobile. Thus, the two fresh-water samples lost water slightly faster than the salt-water samples and those with large particles lost more than the Mobile sample, which had the largest fraction of clay-size particles.

Vertical shrinkage curve

109. The vertical shrinkage curve for the dredged material is shown in Figure 75. For the first 8 days, while moisture loss equaled potential, shrinkage was nearly linear and equal for all materials. After that, loss of height per day asymptotically decreased at

different rates. By the end of the measurements, the 33-cm initial layer of each material lost 7.3, 7.5, 9.2, and 10.5 cm for the Philadelphia, Norfolk, Toledo, and Mobile materials, respectively. The total loss of moisture and total shrinkage from the different materials were not ranked in inverse order as one might expect if shrinkage is simply a loss of water. The differences may be a result of the surface layers of some of the materials reaching moisture contents below which shrinkage was no longer linear.

Moisture content profiles during drying

110. The moisture content data taken during Experiment B in the field are shown in Figures 76 - 79. For all the material but the Mobile sample, moisture loss was nearly linear over the time during which data were taken at all depths. The rate of moisture loss from the Mobile sample decreased with time and, by the end of the drying period, the material had nearly reached the moisture content at which the other materials began. The apparent inconsistency of data from one time to another may be partially a result of the horizontal variability in moisture content associated with drying along the edges of the cracks. The moisture contents of all samples except Mobile were within 30 percent of each other; the Mobile sample had a typical moisture content range of 50 percent. The entire layer of each material dried rather uniformly.

111. Much of the data from the Norfolk sample show that the moisture decreased rather than increased with depth. This may be a result of salt buildup and will be discussed later. At the termination of the field drying experiment, dredged material samples were dissected and moisture contents were determined on a large number of subsamples. Results are plotted in Figures 80 - 85. The first observation is that below the very thin surface layer, the moisture content in all samples was relatively uniform. Some drying was observed in all samples along the edges of the blocks of material where they pulled away from the container wall. Drying adjacent to the cracks in the center of the material did not, however, have a noticeable influence on the moisture content in most cases.

112. The Philadelphia sample dried to a moisture content of about 11 percent on the surface. This dry layer covered a layer of material only 5 cm deeper that had 4 to 5 times greater moisture content. Conductivity of this dry layer was lowered probably minimizing any further moisture movement to the surface; no cleavage between wet and dry layers was found. The influence of removal of this layer on moisture loss is discussed elsewhere. A similar dry layer was found on the Toledo material, but it had not dried as much as the Philadelphia material. At the time the Toledo material was sampled, the ratio of moisture content at the surface to that at 5 cm was about 1:2 instead of the 1:5 found in the Philadelphia samples.

113. Mobile material was still much wetter than all others when dissected. Although the surface was dryer, no big difference between the moisture content at the surface and that below the surface was found. Norfolk data were entirely different; the greatest moisture contents were found at the surface and generally decreased with depth. These data are consistent with the periodic samples taken throughout the study. The only plausible explanation is that salt accumulated near the surface and held and attracted moisture. To test this hypothesis, electrical conductivity profiles were determined. Results for the two saline materials are shown in Table 6. Salts had accumulated in the surface horizons of both materials, and as suspected, more salt had accumulated in the surface to 2.5-cm layer of the Norfolk material than in the Mobile sample. These salt accumulations develop suctions which are sufficient to draw moisture from lower layers and result in greater moisture contents near the surface than would be evident in salt-free samples.

Influence of Water Table Depth on Evaporative Losses, Experiment C

114. The cumulative evaporation losses from Experiment C are shown in Figure 86. In this experiment, a greater evaporative potential was maintained. The mean moisture loss from the free-water surface was 0.9 cm/day, representing very hot dry conditions. The moisture loss rates for the Toledo and Philadelphia materials slightly exceeded the evaporation from the free water for the first 13-15 days. Losses from the Mobile and Norfolk materials decreased from the potential after about the 4th day and were nearly identical to each other thereafter. After 19 days of drying, the amounts lost were ranked in the same order as from Experiment A after the same period of drying with the exception that in Experiment C, Mobile and Norfolk materials lost nearly the same amount of moisture.

115. The suctions read on the tensiometers were converted to the height of a water column. Moisture losses for each material (as a percentage of the loss from the freely evaporating water) are plotted in Figure 87 as a function of the suction with the surface used as the zero suction reference. The curves may thus also be interpreted as the depth to the water table water. As long as free water was available in the container bottom, evaporation from all materials proceeded at the same rate as free water; however, once their moisture supply was ended, materials began to dry, increasing the suction. The results for all materials except Philadelphia are shown in Figure 87. The Philadelphia sample cracked parallel to the tensiometer and insufficient data were collected to provide a definite curve. The Toledo sample was able to sustain an evaporation slightly greater than potential until the water table dropped to 120 cm below the surface. This is similar to the results reported by Gardner et al. (1958) and Ripple et al. (1972) for soils. The evaporation from the material from Mobile and Norfolk decreased sharply from potential as the depth to the water table increased. The reason for this rapid drop is not evident.

Influence of Depth of Dredged Material and Subdrainage on Drying Rate, Experiment D

116. Moisture loss curves from containers with drains are shown in Figure 88. The potential loss during this study was low at the beginning, but by the 8th day, potential moisture loss rates were 1.0 cm/day. Throughout the 40 days of measurements, all materials lost moisture at the same rate as the water was lost from the pan. A comparison of these results with those obtained in the more shallow containers in Experiment A indicates that the loss continued much longer at the potential water loss rate from thick layers of materials than from thin layers. The greater reservoir of moisture allows the potential moisture loss rate to continue longer. The cracks had reached the bottom of the deeper containers just before the end of the study; in Experiment A, the material had cracked to the bottom after about 14 days, which indicates the possibility of a relationship between the cracks reaching an impermeable boundary and the time when evaporation decreases below the potential moisture loss rate.

117. The influence of underdrainage on moisture loss can be viewed several ways. Moisture loss through the drain from each material is shown in Figure 89. The Philadelphia material lost the least moisture to drainage followed by the Toledo material, the Norfolk material, and finally, the Mobile material. All the loss rates decreased with time. After 20 days, only the Mobile sample continued to drain. The greatest rate of loss to drainage was 0.2 cm/day for the Norfolk material, while the Toledo material had a maximum loss of only 0.05 cm/day.

118. The cumulative differences between the total moisture loss with and without gravity drainage for the four samples are shown in Figure 90. Initially, the Mobile material in the container without the drain lost slightly more than the material in the container with the drain. However, after 10 days, the Mobile material in the container with the drain lost more moisture than was lost from the undrained container. The cumulative loss difference was small at first

for all materials, but increased sharply thereafter so that, by the end of the study, total cumulative losses were 3 cm greater for the drained Philadelphia, Mobile, and Norfolk materials, and over 7 cm greater for the drained Toledo material. This loss exceeded the drainage loss shown in Figure 89 for which the losses over the same length of time were 0.3 cm for Philadelphia material, 0.7 for Toledo material, 1.5 cm for Norfolk material, and 2.4 cm for Mobile material. Thus, drained materials lost more moisture to evaporation than the undrained material. The total losses are given in Table 7.

119. The differences in losses to evaporation alone are shown in Figure 91. At the beginning of the study for three of the four samples, the cumulative differences due to evaporation were greater in undrained material, probably because the material was wetter. By 12 to 16 days after moisture loss began, the trend reversed and the under-drained material lost more to evaporation. Photographs of the surface of the drained and undrained materials are shown in Figures 92 and 93. The drained material had more and larger cracks. Apparently the drainage induced the formation of wider, deeper cracks through which water evaporated.

Evaporation Influences

Salt crust

120. A group of four barrels of each material were prepared and placed in the environmental chamber in preparation for Experiment B. In the preparation of the Mobile and Norfolk materials, too much sea salt was added to the water in which the material was dispersed. The loss to evaporation is shown in Figure 94 as a percentage of the moisture loss from the free-water surface. Excess salt began accumulating as a white crust on the surface of both the Mobile and Norfolk materials even after 1 day of evaporation. As a result, evaporation from these two materials was less than potential even on the first day of measurements. The loss from the other two samples was similar to that

found in the growth chamber for Experiment A shown in Figure 66. Thus, the influence of the salts on the surface albedo exceeded their influence on the movement of moisture to the surface due to osmotic gradients, in this case of excess salts.

Crust removal

121. The changes in cumulative evaporative water loss before and after the removal of a thin layer of surface crust are shown in Figures 95 - 98 for Philadelphia, Toledo, Norfolk, and Mobile, respectively. For the Mobile and Norfolk materials, no change in the evaporation rates was discernible following the treatment. A small increase in evaporation rates was evident following crust removal from the Philadelphia sample, but after a period of 4 days, the rate returned to its pretreated level. Only for the Toledo sample did a large increase in evaporation rate occur; for several days following crust removel, evaporation from this sample was three times greater than before the crust was removed. By 9 or 10 days after crust removal, the rate of moisture loss was again equal to that before removal.

122. The difference between structural units found in the Toledo material and that of the other materials may explain the results. The Toledo material, when dried, cracked into units 1 to 2 mm thick and typically 8 cm across. These curled upward slightly over a large portion of the surface. In contrast, the other materials dried into a more continuous mass, although occasional flaking was noted. Curling and separating of the crust that occurred in the Toledo material broke the capillary pathways through which moisture could have conducted from the material below. Thus crust removal increased evaporation until a new layer had dried.

123. Enhancement of loss of moisture by removing the surface crust was generally small, even for the one material where it was found, and it is doubtful that it would be economically practical. Removing much thicker layers of dredged material so that a new wet surface is exposed would, of course, begin anew the initial moisture loss rates.

Mixing

124. After a period of drying, the dredged material in one container from each location was removed and broken into pieces with no dimension greater than 10 cm and replaced in the container. The influence of this treatment can be seen in Figures 99 - 102. In all cases, an increase in the rate of evaporative drying was observed and, after 4 or 5 days, the rate of moisture loss had decreased again to the rate before the treatment.

125. At the time the treatment was carried out, the mean moisture contents of the materials were 37.3, 46.6, 123.5, and 138.4 percent for the Philadelphia, Toledo, Norfolk, and Mobile samples, respectively. Had the materials been broken up when they were at greater moisture contents, the increased evaporation may have been greater or lasted slightly longer, but it was still expected that the increase would not be economically justifiable. It is also possible that the disruption of the crust associated with mixing would cause rainfall to more readily penetrate the dredged material, and that the drainage cracks would be blocked, thus offsetting any benefit of mixing.

Influence of Rainfall on Rate of Moisture Loss and Volume Change of Dredged Material

126. One container of each material used in Experiment A was removed from the environmental chamber and placed in the rainfall simulator where they each received 2.5 cm of rain. The excess was drained, indicating an absorption of approximately 1 cm as shown on the 41st day in Figure 66. The moisture absorbed from the rainfall was evaporated over the next 6 days. The rate of evaporation was essentially the same as that which prevailed during the period immediately before the rainfall and was 1/4 of the initial rate from the original wet material. This indicates that the moisture from the rainfall was quickly redistributed in the material and free moisture remained at the surface for only a very short time.

127. Shrinkage before and after rainfall for each material is shown in Figure 67. A series of measurements were taken just before and after the samples were moved, rained on, and moved back to the environmental chamber. All of these measurements indicated no immediate influence on the shrinking or swelling of the material. For three of the four samples, the shrinkage during the period following rainfall occurred at faster rates than was found prior to the rainfall. This spurt of shrinkage was not correlated with an equivalent increase in moisture loss rate. Thus, it appeared that the temporarily rewetted material underwent additional decreases in volume resulting from evaporation of rainwater.

Rewet Experiment

128. The moisture absorbed during the flooding of the dried dredged material is shown in Figures 103 and 104 for the initially dry and initially wet materials. Initially, dried dredged material had surface moisture contents of 6.8, 8.1, 4.6, and 6.2 percent for the Philadelphia, Toledo, Norfolk, and Mobile samples, respectively. The Toledo material reabsorbed more moisture than any of the others, and the initial reabsorption rate was very large. The flakey, porous surface contributed to the reabsorption. Absorption by the Philadelphia sample was slower and less total water was absorbed. The Mobile material absorbed the least moisture. For all the materials but the Norfolk, most of the reabsorption occurred during the first 10 hr and reabsorption ceased after 24 hr. The Norfolk sample continued to absorb moisture at a low rate continuously during the 125 hr of observation. The wetter samples had initial moisture contents of 72 and 28 percent for the Toledo and Philadelphia materials, respectively. Both continued to absorb moisture at the rate of about 0.006 cm/day. As would be expected, the wetter materials reabsorbed much less moisture than the drier samples. In most cases, the drier samples stopped reabsorbing moisture after 24 hr, while the wetter samples continued to absorb moisture at a very slow

rate. The amounts of moisture reabsorbed by all materials were very much less than the amounts that were lost during the previous drying. For Mobile, reabsorption was about 30 percent of that lost during the drying. The Toledo sample regained about 7 percent of that lost to evaporation.

129. Thus, reabsorption occurred within a short time of flooding and was small compared to previous evaporative losses. The hysteresis in moisture retention may be attributed to the formation of structural units which hold less moisture at equal potentials than did the original material. The curves of the swelling of the material are shown in Figures 105 and 106. Swelling was small in all cases and occurred slower and over a longer period of time than did reabsorption. When the data are compared, it is evident that the amount of swelling for most samples was related to the amount of moisture taken up. The exception is the Mobile sample, which swelled only slightly at first, but then swelled more rapidly and reached a plateau after 100 hr of flooding. The difference can be attributed to the large amount of swelling clay in this material. Apparently some time was required before the moisture caused the clay particles to swell.

130. These results indicate that rainwater will be rapidly absorbed by the materials initially, but after a day, absorption will be very much lower. Surface drainage will need to carry the water off rapidly to prevent reabsorption. Increases in volume due to flooding are very small. Thus, flooded or buried material dried to some moisture content will not absorb much water nor will they reswell significantly.

131. The cracks which were present in the material at the time of flooding remained open throughout the 7 days of flooding and did not swell shut. This observation is in agreement with field observations that when partially dried materials are flooded, cracks remain.

132. The distribution of moisture in the material which had been submerged for 6 days is shown in Figures 107, 108, and 109 for the material which had been rewetted at the initially dryer content, and in Figures 110 and 111 for the initially wetter material.

133. For the initially dry materials, greater moisture was found along the top and edges, but the cracks in the Philadelphia sample (Figure 107) did not seem to result in marked increase in moisture content via lateral intrusion. The greater moisture content found along the bottom of the samples may be due to the material wetting from below as well as from above. Assuming initial moisture content distributions were similar to those shown in Figures 80 - 85, it is evident that the then dry layer at the surface absorbed much of the moisture taken up and little moisture was absorbed by the material in the center of the blocks.

134. When initially wet samples were rewet, moisture contents at the surface remained lower than those near the center of the material. Apparently, once the Toledo and Philadelphia samples had dried at the surface, the moisture content, upon resaturation, was less than that held initially. These figures also indicate that the conductivities were low and moisture was not rapidly transmitted into the material.

Influence of Environment on Evaporation

135. Samples of material from each location were dried in the growth chamber (Experiment A) and in the field during two different periods (Experiments B and C). Comparison of the data from these three experiments provides an opportunity to demonstrate the dependence of evaporation rate on the climate. The growth chamber climate represented an extremely dry condition with constant high evaporation rates, while the field conditions represented low to medium evaporation rates. For purposes of comparison, the data were converted to a ratio of evaporative loss from the dredged material to that from the free-water surface. The results are shown in Figures 112 and 113 for the material from Mobile and Philadelphia, respectively. A comparison of the results in the shallow barrel indicates that for both samples evaporation decreased rapidly from 100 percent of the pan loss and that it was similar in both environments. As would be expected,

during the second stage of drying, the evaporative losses were decreased and independent of the environmental condition. Throughout the measurements on the deep barrel, the evaporative losses nearly equaled the potential, thus indicating that the moisture supply was sufficient to never limit the evaporative loss throughout the study.

136. The moisture in the thin layers of material used in Experiments A and B evaporated at the potential for only 5 to 10 days, after which the losses decreased since they were not resupplied from below. The thicker layer continued at the potential for at least the 40 days of the experiment even without the presence of a water table. The break between the first and second stage of drying for the dredged material appeared to occur when the materials cracked to the bottom of the containers. This occurred after 5 to 10 days in the shallow containers and did not occur until the very end of the measurements in the deep containers.

Calculation of Surface Drainage

137. A computation of surface drainage can be divided into expressions to calculate buildup of water during a storm and those representing drainage of water over a weir. These will be developed and utilized to calculate time required to drain confinement areas of different sizes with weirs of various lengths when rainfall occurs at different rates. Since drainage can be enhanced by trenches cut in the dredged material, procedures are presented for sizing trenches as well as for determining the slope stability of the material.

Water buildup during storms

138. To compute spacing of drainage trenches over the nearly horizontal drainage area, buildup of water during a rain must be computed. From the equation of continuity, it can be seen that:

$$A\int_0^{h_1} dh = A\int_0^{t_1} R_r dt - \int_0^{t_1} q_d dt \qquad (2)$$

where: t = time in seconds

t_1 = duration of rainstorm in seconds

A = drainage area in square metres

h = height of water in metres

h_1 = height of water at end of rainstorm

R_r = rainfall rate in metres per second

q_d = flow rate over weir out of drainage area in cubic metres per second, and also

$q_d = CWh^{3/2}$ for the flow over a broad crested weir in cubic metres per second, where

C = a coefficient for the weir with dimensions of metres to the one-half power per second, $\sim 2.05 m^{1/2}/sec$

W = width of weir in metres

139. Differentiating Equation 2 with respect to time and divid-

ing through by A produces:

$$\frac{dh}{dt} = \frac{2.05W}{A}\left(\frac{R_r A}{2.05W} - h^{3/2}\right) \tag{3}$$

140. When variables are separated, integration will result in:

$$\int_0^{h_1} \frac{dh}{\frac{R_r A}{2.05W} - h^{3/2}} = \frac{2.05W}{A}\int_0^{t_1} dt + C \tag{4}$$

where initial conditions h = 0 when t = 0 will allow C the integration constant to be evaluated. The other boundary condition requires that $t = t_1$ when $h = h_1$ at the end of the rainstorm.

141. A transformation of variables will make the above equation integrable. Let:

$$(-b)^3 = + \frac{R_r A}{2.05W} \tag{5}$$

where b has the dimensions of metres to one-half power, and

$$z = h^{1/2} \tag{6}$$

or

$$z^2 = h \tag{7}$$

where z has the dimension of metres to the one-half power. Differentiation of this last equation gives:

$$2z\, dz = dh \tag{8}$$

142. These substitutions allow the above integral to be re-written as:

$$\int \frac{2zdz}{-b^3 - z^3} = \int \frac{2.05W}{A} dt + C \tag{9}$$

143. Integration, as shown in Appendix C, gives:

$$t = \frac{2A}{9bW} \quad \ln(b + z) - \frac{1}{2} \ln(b^2 - bz + z^2)$$

$$- \quad 3 \text{ arc tan } \frac{2(z - b/z)}{3 \ b} + D \tag{10}$$

where D is the integration constant to be determined from initial condition t = 0 when h = 0 or z = 0. These conditions yield:

$$D = -\ln b + 1/2 \ln b^2 + 3 \text{ arc tan } (\frac{-1}{3}) \quad \frac{-2}{3} \frac{b^2}{R_r} \tag{11}$$

144. Substitution of D into the integrated equation gives:

$$t = \frac{-2b^2}{2.05R_r} \quad \ln(\frac{b + z}{b}) - \frac{1}{2} \ln(\frac{b^2 - bz + z^2}{b^2})$$

$$-\sqrt{3}(\text{arc tan } \frac{2z - b}{3 \ b} - \text{arc tan } \frac{-1}{3}) \tag{12}$$

145. The final condition requires that $t = t_1$ when $h = h_1$; therefore,

$$t_1 = \frac{-2b^2}{2.05R_r} \ln \frac{b + z}{b} - \frac{1}{2} \ln \frac{b^2 - bz + z^2}{b^2} -$$

$$\sqrt{3}(\text{arc tan } \frac{2z - b}{3 \ b} - \text{arc tan } \frac{-1}{3}) \tag{13}$$

with the dimensions of seconds, but it must be remembered that:

$$z_1 = h_1^{\frac{1}{2}} \tag{14}$$

with dimensions of $(\text{metres})^{\frac{1}{2}}$, and:

$$(-b)^3 = \frac{R_r A}{2.05W} \tag{15}$$

with dimensions of $(\text{metres})^{3/2}$, so that at the end of storm of duration t_1, and intensity R_r, the height of water standing over the area A will be h_1 when the weir width is W.

146. It is well known that the shorter the rainstorm duration, the greater the rainfall rate that can be expected. This relationship was studied by David C. Yarnell as reported in the classic paper by Hathaway (1945). Figure 114 is reproduced from Hathaway's 1945 paper. It gives Yarnell's curves that relate rainfall intensity to storm duration. The curve numbers correspond to the one hour storm that could be expected at a site.

147. R. E. Schiller of the Civil Engineering Department, Texas A & M University, determined the equation of these curves of Yarnell. It is:

$$R_r = 42.5 \exp(0.075\sigma) \quad t_1 + 10^{-0.9\sigma^{-0.26}} \tag{16}$$

where: R_r = rainfall intensity in inches per hour

σ = one hour rainfall in inches

t_1 = duration of rainfall in minutes

148. In order to determine σ, the Weather Bureau map of the worst expected one hour rainfall (two year frequency) is reproduced as Figure 115. Should it be necessary, lower frequency storms could be considered; however, since lives are not endangered, the two year frequency storm seems sufficient.

149. For design purposes, the storm duration t_1 or buildup time can be taken as the mean storm duration t_m at a given locality (Soil Conservation Service, 1973).

$$t_m = S\ P_p \tag{17}$$

where: t_m = mean storm duration in hours

S = a coefficient about equal to 0.43 for summer-time storms

P_p = average annual precipitation in centimetres

150. The area A and the one hour intensity of rainfall σ are determined by topography and locality. The value of t_1 can be calculated from Equation 17 because the yearly precipitation is a well-known parameter for each locality. Knowing t_1 and σ, the rainfall rate R_r can be calculated from Equation 16 or taken from Figure 114. The buildup Equation 13 and the intensity Equation 16 were computerized as shown in Appendix C. By assuming a value of W for the weir width and taking a series of values for h_1, the buildup time t_1 can be computed. The correct value of h_1 is the one that gives t_1 same as computed from Equation 17. This same process can be repeated for many weir sizes to develop a relationship between h_1 and W once A, σ, and t_1 are fixed.

Drainage

151. The time required for the water stacked up over the confinement area to drain off through the weir may be computed as follows using again the continuity equation:

$$Ah_1 - Ah = A\int_{t_1}^{t} e_v dt - \int_{t_1}^{t} q_d dt \tag{18}$$

where: e_v = evaporation rate

$q_d = 2.05Wh^{3/2}$ = drainage rate over a broad crested weir as given before in cubic metres per second

A = area of drainage in square metres

h_1 = height of water standing on the site at the end of the rainstorm in metres when t equals 0

h = height of water at any time t in metres

t = time in seconds

t_2= time for drainage when h equals 0

152. This drainage equation is similar to the buildup equation and can be solved the same way, but if the evaporation rate is small in comparison to the drainage rate over the weir, then:

$$Ah_1 - Ah = -\int_{t_1}^{t} q_d dt \tag{19}$$

153. Differentiating with respect to time gives:

$$A \frac{dh}{dt} = q_d = 2.05Wh^{3/2} \tag{20}$$

or

$$\frac{dh}{dt} = \frac{2.05W}{A} h^{3/2} \tag{21}$$

Separation of variables produces:

$$\int \frac{dh}{h^{3/2}} = \frac{2.05W}{A} \int dt + C \tag{22}$$

where C is the constant of integration. Integration gives:

$$-2h^{-\frac{1}{2}} = -2h_1^{-\frac{1}{2}} \tag{23}$$

The initial condition's requirement is that t = 0 when h = h_1 or:

$$C = -2h_1^{-\frac{1}{2}} \tag{24}$$

Combining, it is seen that:

$$t = \frac{2A}{2.05W}\left(h_1^{-\frac{1}{2}} - h^{-\frac{1}{2}}\right) \qquad (25)$$

The final condition requires that $t = t_2$ when $h = 0$, therefore:

$$t_2 = \frac{2A}{2.05W}\ h_1^{-\frac{1}{2}} \text{ in seconds} \qquad (26)$$

154. This last equation was also computerized as shown in Appendix C, using h_1 as determined by the simultaneous solution of the buildup and intensity equations. The total time T the site is inundated is the sum of the buildup time t_1 and the drainage time t_2 or:

$$T = t_1 + t_2 \qquad (27)$$

Because t_1 is relatively insensitive to the weir width W, the total time of inundation T is a hyperbolic function of W when all other parameters are held constant; therefore, there is a practical weir width for which the time of inundation does not increase very much. This is illustrated in the following example problem:

<u>a</u>. Select A = 50 Ac from site topography.

<u>b</u>. Select σ = 2 in. from Figure 115 and the site location.

<u>c</u>. Select P_p = 33.63 in., the local annual precipation.

<u>d</u>. Determine t_1 = (0.17)(33.63) = 5.72 hrs = 343 min from Equation 17.

<u>e</u>. Determine R_r = 0.60 in/hr = 0.05 ft/hr from Equation 16 or Figure 114 using t_1 = 343 min.

<u>f</u>. Assume W = 25, 50, . . . , 200 ft. Using the computer code for Equation 13 as given in Appendix C, compute the buildup time t_1 for values of h_1 taken as 0.1, 0.2, . . . , ft. These figures are shown in Table 8.

<u>g</u>. Determine the value of h_1 that corresponds to t_1 found in Step e. It is seen that h_1 = 0.285 ft for all weir widths.

h. Compute t_2 using the computer code for Equation 26 for all weir widths. These values are shown in Table 8.

i. Compute $T = t_1 + t_2$ for each weir width. These values are also shown in Table 8.

j. Determine W = 150 ft because additional weir width does not appreciably change T.

155. The total time required to completely drain a perfectly smooth, graded site, even under moderate to severe rainfall conditions, is relatively rapid and on the average does not exceed more than a few days even under the worst conditions. Under normal conditions, this drainage will be achieved in less than half a day from a smooth site. Construction of a single drainage trench down the middle of the site would reduce this time to less than an hour.

156. Influence of cracks in the dried crust was not analyzed here because of the complexities of the problem. Such cracks would probably slow the runoff because of the tortuous paths required to reach the trench. Just how much remains unknown, however.

157. The important concept here is to keep the site dry to facilitate evaporation and consolidation. The short time which rainfall is present on a smooth, graded site should not adversely affect this process. The problem lies with the poorly graded site containing numerous depressions and "potholes" which allow water to accumulate and remain on the surface for considerable period of time, thus prohibiting evaporative consolidation. Proper grading and elimination of depressions is mandatory if consolidation and dewatering of dredged material is to be accomplished.

Sizing trenches

158. Assuming that flow into a ditch from a horizontal surface can be modeled by the weir formula, then:

$$Q_i = 4.10 \, L \, h^{3/2} \tag{28}$$

where: Q_i = flow into ditch

L = length of ditch in metres

h = height of water flowing into ditch in metres

The constant in the left side of the formula is twice the coefficient for a weir formula because there is a flow into the ditch from both sides. Also, if the discharge out of a ditch with a flat bottom can also be modeled with a weir formula, then:

$$Q_o = 2.05\ W\ H^{3/2} \tag{29}$$

where: Q_o = flow out of ditch

W = width of weir or ditch bottom in metres

H = height of water in ditch in metres

Because of continuity, Q_o equals Q_i. Equating the two flow rates, the width of the ditch bottom can be found to be:

$$W = (2L)(h/H)^{3/2} \tag{30}$$

Example problem

159. Assume that H_{max}, for stability purposes, is .91 m. The size of the site is 647,520 sq m, thus L = 805 m. Also a 5.08 cm water buildup is allowed over the area. Then:

$$W = (2 \cdot 805)(\frac{0.0508}{0.91})^{3/2} = 21.24\ m$$

If the ditch excavation proceeds in steps so that the side slope of 20^o is maintained until a ditch 3.66 m is reached, the required bottom weir width is:

$$W = (2)(805)(\frac{0.0508}{3.66})^{3/2} = 2.63\ m \tag{31}$$

Thus, the excavation procedure based on the above conditions would be as shown in Figure 116 and the trench, starting at an initial width of 21.34 m, could be excavated to a final depth of 3.66 m in four stages.

160. As the material dries out, it will gain strength maintaining a more stable slope. Should a failure occur in the natural material, it will be a slow, progressive failure and will not pose any danger to workmen or the drainage system as the trench would be of sufficient width to allow a certain degree of failure. After failure, the trench will be in a more stable condition.

161. Under specified rainfall conditions, the trench for any given site can be sized. The initial trench width could be reduced by fifty percent if it is open at and sloped to both ends. The final size of the trench is a function of thickness and stability of dredged material.

Slope stability evaluation

162. Without proper field exploration and sampling, stability of the material can only be estimated. If it is assumed that the angle of shearing resistance ϕ is zero (that is, all the soil strength lies in its cohesion), then measured shear strength is equal to cohesion c. This would approach reality for the worst condition of unaltered material. When this material dries, it gains an angle of shearing resistance, shear strength climbs, and it becomes a more stable material.

163. By use of the limit analysis-stability number approach (Winterkorn and Fang, 1975), the maximum depth to which a trench can be excavated H_{max} can be estimated by the equation:

$$H_{max} = \frac{N_s c}{\gamma} \tag{32}$$

where: N_s = stability number at various slope angles β and angles of shearing resistance as shown in Figure 117

c = cohesion

γ = unit weight of soil

Example problem

164. For example, let $\phi = 0$, and assume γ equals 1281.6 kg/m^3, β equals 20°, and c equals 244.1 kg/m^2. Then for β equal to 20°, N_s would equal 6.787 as determined from Figure 117. The depth of the ditch for which slope failure could be expected is:

$$H_{max} = \frac{6.787 \cdot 244.1}{1281.6} = 1.29 \text{ metres}$$

Note that the slope angle of 20° corresponds with that selected for the trench. The unit weight is fairly representative of the material and the cohesion is for the worst conditions (Table 3). The material is anticipated to behave plastically; so as trench construction proceeds, bulging, progressive deformation, and possibly an occasional slide may occur. As previously mentioned, such instability is not critical to the purpose of the trench and will probably decrease as the material dries.

Subsurface Drainage

165. The required trench spacing (or underdrain pipe) was calculated using the formula:

$$S = \sqrt{\frac{4km^2}{q}} \qquad (33)$$

where: S = pipe spacing in metres

k = coefficient of permeability in centimetres per second

m = maximum vertical distance between level of drainage pipes and phreatic surface in metres

q = $\frac{nc}{t}$ equals rate of water drainage downward to the required phreatic surface in centimetres per second

n = porosity

c = vertical distance from initial water table down to phreatic surface

t = time required to lower water table down to phreatic surface

A general description of this method is given in the Soil Conservation Service Handbook, Drainage of Agricultural Land (1973). The above spacing formula is mistakenly given on page 44 of the Handbook as:

$$S = \frac{4km^2}{q}$$

Results of the calculations are shown in Table 9. A better treatment of this problem is given in Harr (1962) which describes the soil drainage problem subject to infiltration using Dupuit Theory of unconfined flow.

166. The permeability of the saturated Norfolk sediment was found by direct test to follow a power law:

$$k = 1.39 \cdot 10^{-4} n^{12.84} \qquad (34)$$

where: k = permeability in centimetres per second

n = porosity

The data points and this curve are shown in Figure 60. From the mineralogy and Atterberg limits (Tables 2 and 4), it can be seen that the three other materials are less permeable than the Norfolk sediment.

167. It is evident that subsurface drainage to ditches by drain pipes would be impractical. Water table reduction can only be accomplished through surface drainage and evaporation through the crust.

Equipment for Removing Dredged Material From Confinement Sites

Mobility problems

168. In order to facilitate drying, it may be necessary to remove or rearrange some of the material from the confinement areas. The mobility of equipment on the dredged material site is dependent on bearing pressure.

169. The relationship of shear strength to moisture content is shown in Figure 118. The maximum shearing stress developed beneath a loaded circular surface area is given by:

$$\tau_{max} = \frac{\Delta\sigma_1 - \Delta\sigma_3}{2} \qquad (35)$$

where: τ_{max} = maximum shearing stress

$\Delta\sigma_1$ = change in major principal stress due to surface load

$\Delta\sigma_3$ = change in minor principal stress due to surface load

The values of $\Delta\sigma_1$ and $\Delta\sigma_3$ are given for points in surface loaded elastic media in most soil mechanics text books, for instance Lambe and Whitman (1969). If the applied bearing pressure is 1400 kg/m^2, it will be seen that at a depth of about 0.4 the width of the track:

$$\tau_{max} = \frac{\Delta\sigma_1 - \Delta\sigma_2}{2} = \frac{0.82 - 0.18}{2} (1400 \ kg/m^2)$$

$$= 448 \ kg/m^2 \qquad (36)$$

Thus, it can be seen from Figure 118 that if the Norfolk material (salt water) can be dried through evaporation to a moisture content of 60 percent, it will develop a shear strength of 500 kg/cm^2. This exceeds the maximum shear stress developed by a tracked vehicle that applies 1400 kg/cm^2 to the surface. However, this maximum stress is developed at a depth of about one-half the width of the track; therefore, the drying must reach this depth before the vehicle can be supported.

Conventional equipment

170. The first and most economic approach is to use conventional equipment. Godwin (undated) evaluated the feasibility of such equipment, concluding that the bearing capacity of the crust and underlying material was too low to support conventional draglines, backhoes, etc.

171. Green and Rula (1974) evaluated 57 pieces of low-ground-pressure construction equipment. The following three criteria were used to evaluate the vehicles to determine if they were capable of operating in dredged material:

a. The vehicle will operate successfully in the softest soil encountered

b. The vehicle will operate on both land and water

c. The loaded ground pressure is less than 2109.3 kg/m^2.

172. The nine vehicles selected were as follows:

a. Amphicat - inexpensive but capable only of transporting personnel or surveying equipment.

b. Marsh Screw Amphibian - useful only for personnel transport.

c. Ditcher Model 104T-DSP-70 - ditching machine for narrow ditches.

d. Riverine Utility Craft (RUC) - personnel and cargo transport with light drilling capability. (Not commercially available)

e. XM759, Cargo Carrier - cargo carrier with light drilling capability.

f. Amphibious Carrier Model No. 104-W-HD-59 - cargo carrier with light drilling capability.

g. Dragline Carrier Model No. 10XT-HD-59M - dragline and drilling capabilities.

h. Roto-Boom Model 104T-65 - drill rig and clam shell capabilities.

i. Dragline Carrier Model 16Xt-HD-2E-73 - dragline and drill rig capabilities.

All vehicles except the first was track or helical screw mounted. It appeared that the dragline carriers could be modified to provide a light weight pile driver for placing sheet piling. The only other wheeled vehicle that offered certain possibilities as a cargo hauler was the Rolligon 8860. However, it did not rate well in very soft soils.

173. Some of the schemes suggested in the following section for water removal require dredging of material within the containment site. National Car Rental's Mud Cat Model MC-15 (Figure 119) seems the most suitable piece of equipment. It measures only 2.44 m wide and 9.75 m long and has a 4.57 m digging depth. Its dredging capacity is between 61.2 and 76.5 cu m/hr, and it could be used to move wet material within the confinement area.

174. Because of the instability of partially dewatered dredged material, no equipment is available to haul suitable loads of material from a drėdged site. As will be suggested in one of the schemes to follow, small barges may be of value in transporting either the material dredged with a Mud Cat or material that has been dried from the confinement area. The draft and capacity of barges are well known and will not be considered here.

Possible Schemes for Managing Dredged Material Confinement Areas

175. With the intent of reducing the volume of material contained in dredged material disposal sites, two approaches were available: remove the material or remove the moisture. Material removal required equipment capable of operating on the soft, weak dredged material. In any event, some moisture must be removed or else the problem is not solved, only transferred. The second approach seems to be more acceptable as several schemes can be promoted for water removal and subsequent rehandling of the dried dredged material if necessary. Only the schemes which appear practical will be considered in detail.

Scheme I: Dredge the material stored in an old site and pump it to a new location further inland, depositing it in thin layers which are allowed to dry before they are covered with a new layer. This scheme is not considered economically or practically feasible.

Scheme II: Pump the material underlying the crust on to the top of the crust to allow evaporation. No pump could be found which could handle materials with the properties of the in-place dredged material. If a pump could be found, it could be skid-mounted and dragged across a site by a winch and cable. An analysis of energy requirements showed that between 22,000 and 44,000 abs. joule sec^{-1}/30 cm for 15-cm-diam pipe would be required to move 1 cu m of dredged material in its natural state; this included lifting it an elevation of 1.5 m. This is considered uneconomical.

Scheme III: Lower the water table by a system of trenches and provide surface drainage for rainfall. This would allow rapid runoff of storm water. Depressions and low spots should be filled by material dredged from the trenches and future dredging. It is recommended that the present outfall pipe be replaced with a slotted pipe running the length of the site along the dike so that dredged material will be deposited more uniformly and flow towards the drainage trench system.

176. Any surface drainage trench that is constructed by indentations such as those created by the RUC will be limited because drainage of water into the trench will be inhibited (Figure 120). A double indentation trench, with material stockpiled in between, would be the best option if such equipment is to be used (Figure 120). A dredge seems to be the only way to efficiently move wet material because the material sticks to anything coming in contact with it.

177. There are several possible approaches to Scheme III, one of which is the use of sheet pile trenches as follows:

Construct sheet pile trenches and allow the material to drain and consolidate naturally. Time required for 90 percent consolidation is considerable, but consolidation may be shortened through the injection of horizontal sand layers (Lytton, 1976).

Sheet pile drainage could be used to remove surface and some subsurface moisture.

Any pile-type drainage system would be very costly, and it is doubtful that it would be cost effective.

178. The excavation of trenches could be accomplished using either a dragline carrier or Mud Cat. Possibly, only a single-trench system down the middle of the site would be required if proper site grading is maintained. Should a slope failure occur, it will not impede trench construction but must be graded to a smooth surface. This system appears to be the most economical solution to dewatering and densification of a confinement site as only earth-moving equipment and possibly a few sump pumps are required. Once densification is achieved, the site can be leveled and compacted making it ready to receive new dredged material in a controlled deposition-evaporation process.

179. Material dredged or excavated from the trench should be deposited far away from the trench edge so that flow back towards the trench would allow material to settle out of solution filling in existing depressions and forming a smooth slope towards the trench. A temporary, movable wooden barrier may be required to facilitate sedimentation and decantation. If more than one trench is required, material should be deposited along the center line between trenches.

Example Reclamation and Management Procedures

180. The following discussion is presented to demonstrate management procedures recommended for reducing material volume and moisture content on a site (Scheme III), coupled with removal of dried crust material from the site. A brief summary of factors involved in making these decisions precedes the detailed excavation plan.

Factors

181. For the purpose of this example, a hypothetical 64-ha site with a square configuration was selected. Side length was taken as 805 m. Depth of the material in the site was assumed to be 4 m.

182. Equipment used for excavation was only for example purposes. Equipment with equal or greater capabilities would be suitable. The Mud Cat is a small dredge capable of moving 76 cu m of material/hr

with a dredging depth range in excess of 4 m (Appendix D). The dragline mounted on a carrier had an assumed boom length of 25 m and a ground-bearing pressure of under 1400 kg/m^2. Its casting distance was taken as 25 m with an unloading distance of 20 m (Havers and Stubbs, 1971). The maximum shearing stress exerted by the dragline was about 450 kg/m^2. Therefore, the soil must achieve a design shear strength of at least 500 kg/m^2 to avoid failure. As the dragline is fully buoyant, settlement into the material was not considered a problem.

183. Since no mobile equipment was available to haul dried material off the site, a barge was selected. Any size barge, either self-powered or cable-powered, capable of operating fully loaded in less than 1 m of water could be used.

184. In order to achieve a shear strength of 500 kg/m^2, the material must be allowed to dry to a 60 percent moisture content for most materials to achieve this strength based on vane shear tests.

185. If a single, 1-m-deep trench were used to handle peak surface drainage from the site being considered, it would have to be at least 20 m wide at the base. With a 20° slope, a trench could safely be dug to a maximum depth of 1.3 m in this soil.

186. Surface drainage is of primary importance in achieving dewatering and volume reduction. Thus, all depressions must be filled and dredged material deposited in such a fashion as to grade the site uniformly toward the trenches. It is recommended that a slotted discharge pipe be used to discharge material along the center line between trenches. A temporary weir can be used along the trench edges to decant the dredged water permitting material sedimentation.

187. The recommended procedure is considered quite economical; however, costs are a function of time, which is dependent on how fast site reclamation is desired. No time-optimization plan is advanced here.

Site reclamation procedure

Step 1. A series of trenches 2 m deep and 10 m wide at the base using one or more Mud Cats; these trenches should be connected by a cross trench, allowing drainage to the center trench with a weir at each end. Two trenches along the dike could be excavated from the dike by a dragline. At this time, flood the trenches to allow dredging. Deposit dredged material between trenches using a slotted pipe to fill in all depressions and to provide a smooth grade towards the trenches for surface drainage. Leave the side trenches between the center trench and dike trenches short of the dike to provide complete access to all parts of the site for the dragline (Figure 121). The center line distance between trenches should be 100 m, which is within excavating limits of the dragline.

Step 2. Drain 1 to 1.5 m of water from the trench systems and allow crust development through evaporation to a depth of 1 m. Some water should be left in the trench to maintain wall stability.

Step 3. Close the weirs and flood the trenches to a depth of 1 m. It has been shown that, once dried, the soil will reabsorb very little water and, although the water table may rise due to the presence of tension cracks, the soil will not revert to its wet, weak, sticky, natural state. Barges can be placed in the flooded trenches. The barge system of transporting excavated crust soil to the dike edge for loading into trucks has been recommended since no other soil-transporting equipment could be found that could traverse the site with profitable pay load.

Step 4. After providing access ramps, draglines would enter the site and, by operating between trenches, excavate crust material and load it onto barges for transport to the dike. The water level in the trenches is maintained to provide a safe operating depth for the barges.

Step 5. Once the crust material has been removed and the draglines have vacated the site, allow the excess water to drain through the weirs, leaving enough water in the trenches for the dredge to operate. Repeat steps 1-4, increasing trench depth by 1-m increments until all material is removed from the site.

Site management procedure

188. Once all the material has been removed, the site is available for reuse. Careful management is mandatory for successful site use. It is recommended that dredged material be replaced in thin lifts allowing time between placing of the next lift for evaporative drying to reduce the moisture content to 60 percent in most cases and pre-

ferably 50 percent. Thus, it may be necessary to divide the site into cells so that continuous dredging can proceed. Under no circumstances should the next lift be placed until the first lift has dried. If this procedure is followed, once the site has filled, only conventional earth-moving equipment would be required if the base is stable. In any case, a drainage trench down the middle of the site must be maintained. Its bottom width should be at least 10 m. As with the reclamation procedure, no surface depressions should be permitted. Material should be discharged along the dike using a slotted pipe to allow a smooth sloped surface to develop toward the trench. If any water is allowed to pond and stand on the site, the material will not dry. In addition, compaction of a dry lift just before placement of the next lift may increase its unit weight and decrease its volume.

PART V: RATE OF CRUST FORMATION

189. The pan and net evaporation shown in Figures 1 - 24 can be used to demonstrate the necessity for proper drainage of confinement areas. The data from the four locations of interest have been summarized in Table 10. For all four locations, if no drainage is allowed, the mean annual precipitation will exceed the evaporation so that the net result will be an accumulation of water. This is obviously the extreme case where no drainage is allowed at all. If weirs were maintained just at or slightly below the level of the confined material, which seems to be the practice in many locations, the net result may be an exact balance between rainfall and evaporation. This would allow the formation of a surface crust during dry periods, but the material below remains wet. This is exactly what is most commonly observed in the field.

190. The other extreme case is represented by pan evaporation. Certainly not all rainfall could be drained before it infiltrated, but if it were, and if dried material would be recovered when it began to restrict evaporation loss, upwards of 80 cm of water could be evaporated in all locations each year. With optimum management, the water losses that can be achieved should fall somewhere between the two extremes.

191. The monthly distribution of potential and net evaporation indicates that although most of the water will evaporate during the summer, it is also important to manage the areas to provide proper drainage during the winter months as well.

192. The pan evaporation data for various locations may be used to evaluate the most rapid rate of water loss from the confined material. The results given here show that the rate at which a dry crust forms is dependent on the evaporative demand of the atmosphere, the thickness of the lift from which water is evaporating, and the depth to the water table. In addition, the rate would, of course, be slowed down each time rainwater is resupplied to the crust. Evaporation takes place in two stages. During the first, the water loss is

dependent on the evaporative potential which may be approximated by the pan evaporation described above. During this stage of drying, the resupply of water from within the material below the surface is sufficient to exceed the water loss. This stage of drying is considered to begin when free water can no longer be decanted from the surface. Two sets of equations were used to describe the relationships for the water content of the surface at this point. These are given in Table 11. Linear equations through the origin and linear equations with an intercept were developed which did not go through the origin for both the liquid limit and plasticity index for the materials which were adjusted to appropriate moisture contents without drying and the same material which had undergone drying, grinding, and sieving as is normally done prior to running the tests. The correlations based on the four samples are best for the liquid limit. The highest correlation is with the linear relation through the axes against the liquid limit of the reconstituted sample. Thus, for convenience, the water content where drying begins is taken as 2.53 times the liquid limit. It should be noted that it is important to use water with appropriate soil concentrations to reconstitute the samples.

193. Similar equations were developed for the moisture content at which evaporation decreased from the potential. Again, the relation selected is that dependent on the liquid limit of reconstituted samples. The moisture content of a 2-cm-thick surface sample at which evaporation rate decreases from the potential is 1.86 times the reconstituted liquid limit for the samples tested.

194. For 30-cm-thick samples, the moisture content reaches this value in about eight days of continuous clear weather drying. For samples 90 cm thick, about 40 days are required of continuous clear weather drying. Cloudy days and the addition of rainfall will lengthen the period. The cracks appear to penetrate the entire depth of the sample at about the time the evaporation decreases from the potential. Without the presence of a water table, it is anticipated that drying will proceed to depths of 120 cm or more. At this time, the data

indicate that the moisture content would decrease rather uniformly from 2.53 times the liquid limit at the 120 cm depth to 1.80 times the liquid limit at the surface. Thus, if one defines the crust as any portion of the material which has undergone a decrease in moisture content, it is anticipated that crusts will form to a depth of 120 cm. Upwards of 60 days of continuous drying without rainfall may be required to achieve this condition.

195. Once the crust has dried to the point where the water supply can no longer keep up with the evaporative demand, the evaporation will decrease gradually. During this period, the entire layer of crust will lose moisture with the surface losing it most rapidly. The decrease is more gradual than would be anticipated for a non-shrinking medium because the surface area exposed as cracks continues to evaporate at the potential. Water will continue to be lost at a slower and slower rate as the material dries. With sufficient time, the surface, if salt free, will finally dry to a fraction of the plastic limit, while material 5 to 10 cm deep will still be between the plastic and liquid limit. For material with salt, the drying is more uniform and a very dry thin surface layer was not observed, probably because the salt had attracted moisture from below and retained it in the soil. Without rain or if all rain is conducted away, it is projected that drying will continue but become insignificant in about a year.

196. The initial part of any management scheme must be a program to insure the rapid surface drainage of rainwater. While the dried material is slow to reabsorb new water and is slow to reswell, the presence of free water will prevent the crust from drying until the free water has been evaporated. The cracks from connecting channels provide passageways through which rainwater can rapidly drain to the ditches. The spacing and design of ditches is being developed in a parallel project and will not be discussed here. Since only small volumes of water will be reabsorbed and need to be reevaporated in properly drained confinement areas, the reabsorbed water should only require a few days to evaporate before drying of the original inter-

stitial water can again proceed.

197. Crust management, including the removal of a thin layer, only appears to have a possible effect once the surface becomes very dry, and the effect would be short lived. The better approach would seem to be to remove the crust to a depth of 1 or 1.2 m once it has dried to that depth. The mixing or agitation of the confined dredged material would have no effect upon the drying during the first stage where the water loss is not limited by the properties of the material. Mixing did, however, have a small but short lived effect during the second stage of drying. It is doubtful that the value could be justified. In addition, although it has not been demonstrated experimentally, it seems obvious that any mixing operation would destroy the cracks which act as natural drainage channels, thus causing more of the rainfall to be collected and trapped. This would ultimately offset the small benefit of any mixing operation.

198. Underdrainage was demonstrated to be effective in removing small volumes of water but resulted in greater rates of water via evaporation, perhaps because of the larger cracks which form. Such results can only be anticipated, however, for drainage systems which underlie the entire area, and these may be uneconomical. Surface drainage is anticipated to be best achieved by the use of a small dredge to cut, reclean, and deepen drainage channels in confinement areas which already contain wet materials. Such operations should begin immediately after the deposition. The data presented here indicate that with proper drainage and lifts of the order of 1.2 to 2 m, it should be possible to reduce the height to one-half or less in a period of a year. The best procedure for a new installation would be to place lifts of the order of 45 cm or less and allow them to dry to about 1/3 of their initial volume before another lift is placed. Proper surface drainage would be required, and the process would be hastened if subsurface drainage were feasible.

PART VI: SUMMARY

199. This study was undertaken to determine the influence of crust management on the evaporative loss of water and densification of confined dredged material. Bulk samples of material were collected from confinement areas at Philadelphia, Toledo, Norfolk, and Mobile. Physical, chemical, and mineralogical properties of the materials were characterized. The influence of evaporative potential on the loss of water from reconstituted dredged material was determined in an environmental chamber and in the field. The influence of management practices including crust removal, breaking up the chunks of partially dried material, controlling the water table, depth of drying layer, and subdrainage was evaluated. The moisture content, suction, conductivity, and unit weight relationships may be utilized to develop a model to simulate the influence of these and other management practices on the densification of the dredged material. Monthly maps of the mean net and gross pan evaporation over the continental U. S. were developed and examples are given of their utilization to predict the water loss and densification as a function of management practices. Volume decreases are equivalent to the volume of water loss for all materials tested. Equations were developed to describe the surface drainage of water from confinement areas over a weir. Schemes were developed to promote surface drainage and assist in lowering the water table. Equipment and systems available for removal of the dried material were evaluated.

200. The material from Mobile differed from the others in that it contained more clay and a significant amount of the clay was the shrinking-swelling smectite type. As a result, it retained more moisture after decantation, dried slower, and shrank more upon drying. Over a wide range of moisture contents, the loss of volume by all the dredged material was identical to the loss of water. When the material became very dry, the loss of volume was less than the volume of water. Dried samples developed structures which caused them to re-

tain less water at identical potentials after they were rewetted. The Atterberg Limits changed significantly depending on the preparation of the samples.

201. Water from the lifts of bulk dredged samples exposed to evaporative environments evaporated at the potential rate for the first 8 to 12 days and the water loss rates decreased asymptotically. If a water table was maintained within a few centimetres of the surface or if the initial layer of material was thicker, the evaporation continued at the potential rate for a longer time. Crust removal and breaking up of the partially dried material resulted in only small increases in evaporation which lasted for a short time.

202. The volume of dried material, when submerged, only increased slightly. The dried material appeared to crack to the water table and the cracks provided channels through which water vapor was lost to the air without passing vertically through the dried material. The direct evaporation from the cracks, which may be equal to 30 percent of the surface area of partially dried material, appears to continue freely and contribute significantly to the water loss.

203. For a new area, the best management practice appears to be placing the material in layers no greater than about 45 cm and allowing each layer to dry before more material is added. In existing areas, the best practice appears to be to promote surface drainage and to lower the water table. In either case, water loss can be promoted by providing one or more sloped drainage trenches to lowered outflow weirs. The maps and tables provided in this report can be used to determine the effectiveness of these treatments at various locations. Sophisticated drainage schemes are deemed too expensive. The most economically feasible system appears to be to dig successively deeper, initially wide drainage trenches with a small dredge. The dredged material can be used to fill small surface depressions and thus enhance surface drainage. It should be possible to dry the material through natural evaporation if the drainage is improved so that the dried material can be removed with conventional equipment if necessary.

PART VII: CONCLUSIONS AND RECOMMENDATIONS

204. The following conclusions and recommendations are drawn from the analysis of the data presented in this report:

a. The first step to achieve volume reductions of confined dredged material after decantation of excess water is to establish and maintain a surface drainage system to conduct rainwater off the drying material. This is true for both new and existing sites. The net evaporation data for the continental United States developed here show that in most districts more rainfall is received in an average year than will be evaporated. A system of drainage ditches should be established, deepened, and widened as much as possible. Such a system should be designed to provide the biggest gradient possible to draw the water off. Periphreal trenching and pumping may be necessary in some confinement areas to intercept and remove water that may encroach from surrounding areas. Weirs must be properly sized to rapidly convey off excess rainwater. A design procedure is given here.

b. Initially, the water is lost at a rate determined by the meteorological factors so no crust management other than that given in a above should or need be carried out. This first stage of drying is complete once the surface reaches a moisture content of about 1.8 times the liquid limit.

c. The evaporation rate begins to decrease from the potential once the surface becomes dryer than 1.8 times the liquid limit, and it is only after this that further crust management may enhance evaporation. Management practices, including stirring and the removal of a thin layer of crust, produced only small increases in evaporation rate for a few days. These techniques would likely not be cost effective and may block the naturally occurring cracks which are essential to proper surface drainage. The presence of vegetation would enhance drying during this stage, but the time required for even indigenous species to vegetate an area may be long compared to anticipated drying times. Therefore, it is recommended that the best and most cost effective procedure is to do nothing until natural drying has reduced the moisture content of the dredged material.

d. For all practical purposes, volume reductions will be proportional to the volume of water loss. Therefore, as water loss slows down, the decision on the timing of the next management procedure will need to be a balance between the value of additional volume reductions and the need for the next deposition on the site under consideration. Data presented here can be used to evaluate the amount of volume reduction which has been achieved and the amount which can yet be anticipated.

e. Once drying is sufficiently complete, two things may be done. If desirable, the surface crust of 1 or 1.5 m thickness can be removed and disposed of elsewhere. This will allow a new layer to begin drying. The second option is to place a new lift on top of the dried crust. Since the shrinkage is nearly irreversible, the old dried crust will reswell only slightly.

f. For most rapid drying and maximum volume reduction, lifts of the order of 60 cm or less should be dried before additional material is added.

g. Underdrainage is an effective management technique provided it is continuous or very nearly so under the entire area. It would be most effective when used in combination with thin lifts. Once cracks open to the underdrainage system, it may also act as a very effective means of removing rainwater.

h. Small cable-anchored dredges appear to be best available equipment for digging wide or deep drainage ditches in confinement areas where conventional drag lines cannot reach from the levees. Small barges could be loaded with drag lines and used to transport dried crust material off confinement areas via temporarily flooded drainage ditches.

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Table 1

Properties of Dredged Material and Water from the Water Table at Various Sampling Locations

Parameter	Source of Sample			
	Philadelphia	Toledo	Norfolk	Mobile
Dredged Material				
Moisture content, percent by weight	70.5	80.0	67.3	120.4
Volatile solids, percent (dry wt basis)	6.3	10.2	6.7	11.8
Total organic carbon, percent (dry wt basis)	2.0	2.3	1.3	2.7
Particle density, g/cm^3	2.55	2.6	2.7	2.55
Reaction with acid*	-	++	++	+
pH	7.1	7.0	7.3	7.3
Water				
Conductivity of leachates, μmho	1420	920	35,200	25,000
Na^+, ppm in leachate	166	12.9	1,784	2,161

*Reaction indicated by the following entries:
- \- no bubbles
- \+ some bubbles
- ++ effervescent

Table 2

Mineralogical Analysis of Dredged Material Samples

Clay Mineral	Source of Sample - Mineral Content, % by wt Philadelphia	Toledo	Norfolk	Mobile
Smectite	3.2	2.0		32.4
Vermiculite	8.6	7.0	7.0	
Chlorite	5.6			
Mica	52.2	55.0	52.0	21.6
Kaolinite	27.5	25.0	36.0	37.9
Quartz	3.0	10.0	5.0	8.0
Feldspar		1.0		

Table 3

Summary of Engineering Soil Properties of Dredged Material

	Vane Shear Test				Shear-Viscometer Test				Permeability Test	
	Fresh Water		Salt Water			Rate of Strain, radians/min-Shear Strength, kg/m^2				
Source of Sample	Moisture Content %	Shear Strength kg/m^2	Moisture Content %	Shear Strength kg/m^2	Moisture Content %	0.8	8.0	80.0	Moisture Content %	Permea-bility cm/sec
Phila-delphia	84.7	177	-	-	64.7	148.7	357.1	515.3	78.2	1.79×10^{-6}
	74.0	407				(fresh water)				
	49.0	2725								
Toledo	74.6	248	-	-	73.6	336.8	346.6	401.6	88.5	5.86×10^{-7}
	61.0	558				(fresh water)				
	50.7	1230								
Norfolk	85.9	336	63.0	474	60.3	555.1	575.1	710.0	76.5	8.71×10^{-7}
	77.3	363	59.6	552		(salt water)				
Mobile	111.4	239	99.7	213	91.9	277.3	436.0	614.6	126.5	4.08×10^{-6}
	141.2	380	85.8	552		(salt water)				

Table 4

Effect of Air Drying on Index Characteristics

Source of Sample	Before Air Drying				After Air Drying			
	Liquid Limit	Plastic Limit	Plasticity Index	Classi-fication	Liquid Limit	Plastic Limit	Plasticity Index	Classi-fication
Philadephia	79.5	42.3	37.2	MH	49.7	35.8	13.9	ML
Toledo	79.7	42.6	37.1	MH	45.7	29.1	16.6	ML
Norfolk	60.7	39.9	20.8	MH	42.0	22.5	19.5	CL
Mobile	115.2	41.6	73.6	CH	85.7	42.8	42.9	OH

Table 5

Comparison of Shrinkage Calculated from the Loss of Height and Volume of 4 Dredged Materials

Source of Sample	Height Shrinkage Percent	Linear Shrinkage* Percent
Philadelphia	18.24	18.03
Toledo	22.50	19.60
Norfolk	24.66	20.13
Mobile	30.1	27.17

Note: Volumes given average of 3 determinations upon oven drying.

*Loss calculated as cube root of volume loss.

Table 6

Electrical Conductivity Matric and Osmotic Suction Profiles In Dried Dredged Material Samples for Mobile and Norfolk

Source of Samples	Depth cm	Moisture Content %	Matric Suction bars	Electrical Conductivity millimhos/cm	Osmotic Suction bars
Mobile	0-2.5	36.5	54.6	100	60
	2.5-5.5	38.5	45.0	64	33
	5.0-7.5	38.8	41.3	50	22
	7.5-10.0	37.0	51.0	38	17
	10.0-12.5	38.4	45.7	36	16
Norfolk		17.1	200	150	<60
		18.0	170	109	<60
		18.2	160	82	55
		17.2	190	70	37
		17.5	175	62	30

Table 7

Water Loss from Dredged Material Samples With and Without Drains

	Source of Sample - Water Loss			
	Philadelphia	Toledo	Norfolk	Mobile
Free-water loss, cm	13.45	13.45	13.45	13.45
With drain:				
Loss to evaporation, cm	12.73	13.24	10.00	9.08
Percent of total	97.5	94.8	87.1	78.3
Loss to drainage, cm	0.32	0.72	1.48	2.51
Percent of total	2.5	5.2	12.9	21.7
Total loss, cm	13.05	13.96	11.48	11.59
Without drain:				
Loss to evaporation, cm	9.91	5.57	7.27	7.43
Difference in total loss, cm	3.14	8.39	4.21	4.16
Difference due to evaporation, cm	2.82	7.67	2.73	1.65

Note: Evaporative data results are the cumulative losses over a 40-day period.

Table 8

Computation for Weir Size for Example Problem

Weir Width															
25 ft		50 ft		75 ft		100 ft		125 ft		150 ft		175 ft		200 ft	
h_1^*	t_1^{**}	h_1	t_1	h_1	t_1	h_1	t_1	h_1	t_1	h_1	t_1	h_1	t_1	h_1	t_1
.15	180	.075	90	.05	60	.1	120	.1	120	.1	120	.1	120	.1	120
.2	240	.15	180	.1	120	.15	180	.15	180	.15	180	.15	180	.15	180
.285	343	.175	210	.18	220	.2	240	.2	240	.2	240	.2	240	.2	240
.35	420	.285	343	.285	343	.285	343	.285	343	.285	343	.285	343	.285	343
.4	480	.325	390	.35	420	.4	480	.4	480	.4	480	.4	480	.4	480
$t_2^{\dagger}$ = 1810		t_2 = 904		t_2 = 602		t_2 = 452		t_2 = 361		t_2 = 301		t_2 = 258		t_2 = 226	
T†† = 2153		T = 1247		T = 945		T = 795		T = 704		T = 644		T = 601		T = 569	

* h_1 = height of water

** t_1 = duration of storm (343 min)

† t_2 = time for drainage in minutes

†† T = time of site inundation in minutes

Table 9

Spacing of Drains to Draw Down Water Table

91 cm in One Year

Percent Porosity n	Void Ratio e	Percent Moisture Content w	Porosity * cm/sec	Downward Flow Rate q** cm/sec	Spacing of Drains S metres
80	4.00	148	7.9×10^{-6}	2.3×10^{-6}	7.90
70	2.33	86	1.4×10^{-6}	2.0×10^{-6}	3.60
60	1.50	56	2.0×10^{-7}	1.7×10^{-6}	1.50
50	1.00	37	1.9×10^{-8}	1.4×10^{-6}	0.49
40	0.67	25	1.1×10^{-9}	1.2×10^{-6}	0.12
30	0.43	16	2.7×10^{-11}	8.7×10^{-7}	0.02
20	0.25	9	1.5×10^{-13}	5.8×10^{-7}	0.002

* $k = 1.39 \times 10^{-4}\, n^{12.84}$ $(\frac{cm}{sec})$ Norfolk sediment (see Figure 60)

** $q = \frac{(n)(C)}{t}$ $(\frac{cm}{sec})$, t = one year

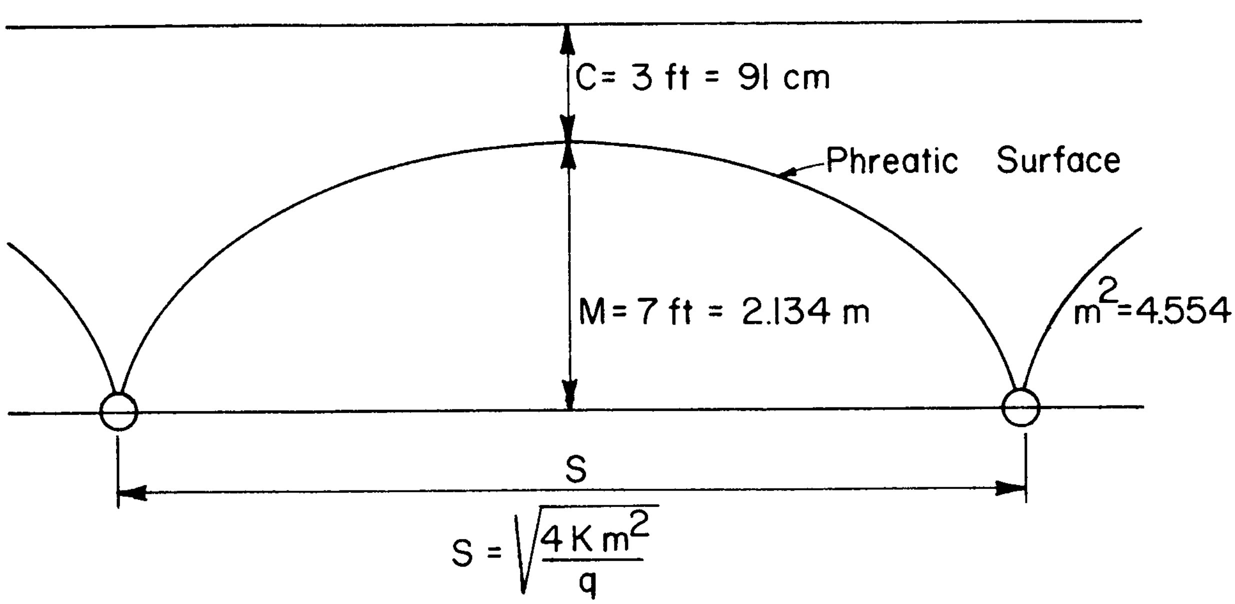

Table 10

Mean Potential and Net Evaporation for Selected Locations in the U.S.

	Location - Evaporation, cm							
	Philadelphia		Toledo		Norfolk		Mobile	
Month	Potential	Net	Potential	Net	Potential	Net	Potential	Net
January	0	- 6.5	0	- 6.2	0	6.0	7.5	- 4.2
February	0	- 7.1	0	- 5.3	0	- 7.5	8.5	- 4.4
March	0	-10.2	0	- 7.5	0	-10.0	10.0	- 6.0
April	0	- 7.7	10.0	- 1.0	10.0	3.0	17.5	- 2.4
May	15.0	2.1	15.0	3.0	17.5	7.0	20.0	3.6
June	17.5	2.9	17.5	4.5	17.5	8.0	20.0	3.0
July	15.0	6.0	20.0	7.5	20.0	7.0	17.5	- 1.0
August	15.0	1.8	15.0	3.0	17.5	2.2	17.5	4.5
September	12.5	1.4	12.5	2.6	12.5	2.0	12.5	0.5
October	7.5	- 0.1	7.5	- 1.0	10.0	0.6	12.5	2.0
November	0	- 9.0	0	- 6.0	5.0	- 7.5	7.5	- 2.5
December	0	- 9.5	0	- 6.0	0	- 9.0	5.0	- 8.5
TOTAL	82.5	-35.9	97.5	-10.4	110	- 1.8	156	-15.4

Table 11

Dependance of Bench Mark Moisture Contents of

Surface on Liquid and Plasticity Index

y_1*	Correlation Coefficient r	y_2**	Correlation Coefficient r
$1.01\ LL_w^{\dagger} + 62.32$	.83	$1.83\ LL_w - 51.91$	.84
$1.23\ PI_w^{\dagger\dagger} + 93.87$	.91	$2.23\ PI_w + 5.20$	.92
$1.53\ LL_r^{\S} + 60.50$	.98	$2.77\ LL_r + 55.11$	.99
$6.09\ PI_r^{\S\S} + 243.80$	.57	$10.03\ PI_r + 260.70$	-.47
$1.72\ LL_w$	.83	$1.24\ LL_w$	.84
$3.07\ PI_w$	.91	$2.33\ PI_w$	.92
$2.53\ LL_r$	.99	$1.86\ LL_r$	.99
$8.77\ PI_r$	-.51	$5.78\ PI_r$	-.47

* y_1 is the moisture content at which water can no longer be decanted

** y_2 is the moisture content at which the actual evaporation begins to decrease for the potential evaporation

† LL_w is the liquid limit of dredged material samples which have not been dried prior to the test

†† PI_w is the plasticity index of dredged material samples which have not been dried prior to the test

§ LL_r is the liquid limit of samples which have been dried and reconstituted prior to the test

§§ PI_r is the plasticity index of samples which have been dried and reconstituted prior to the test

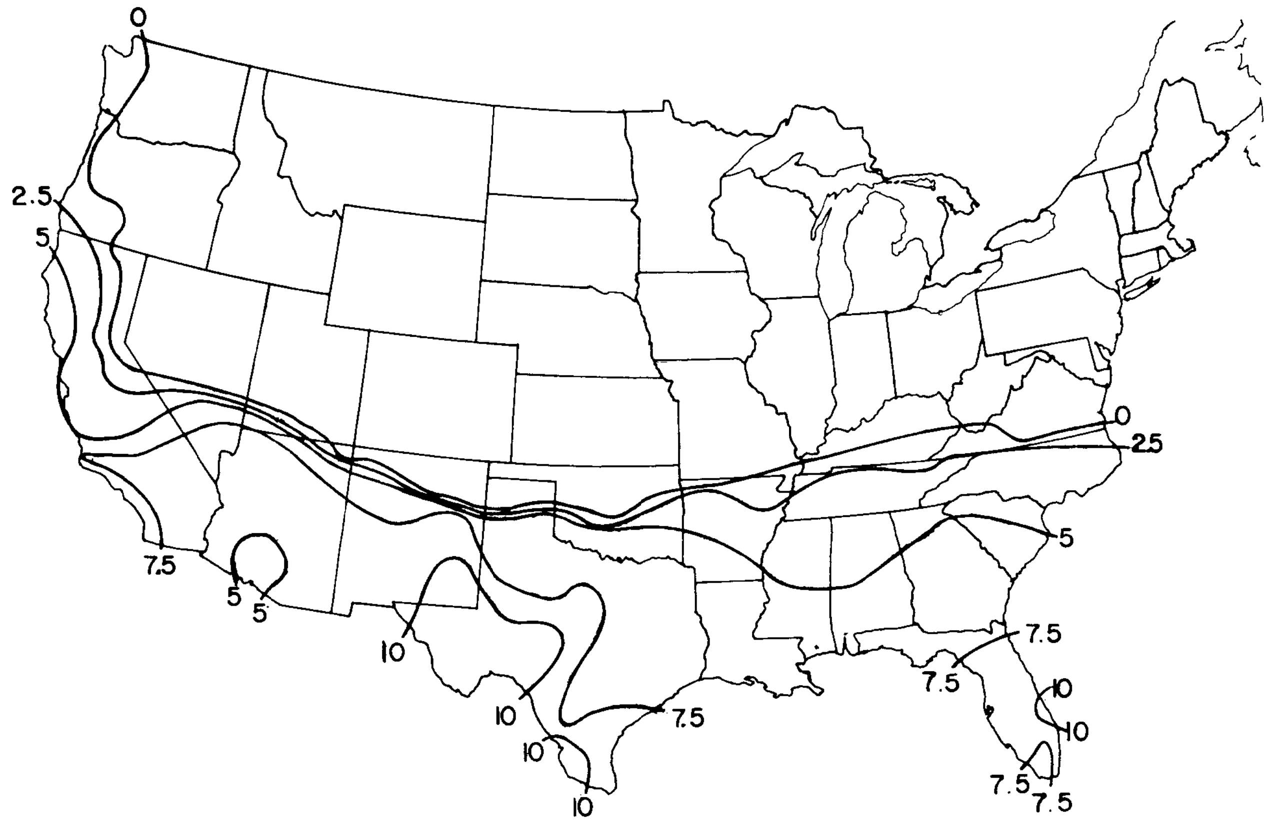

Figure 1. Average pan evaporation in cm for the continental United States for the month of January based on data taken from 1931 to 1960

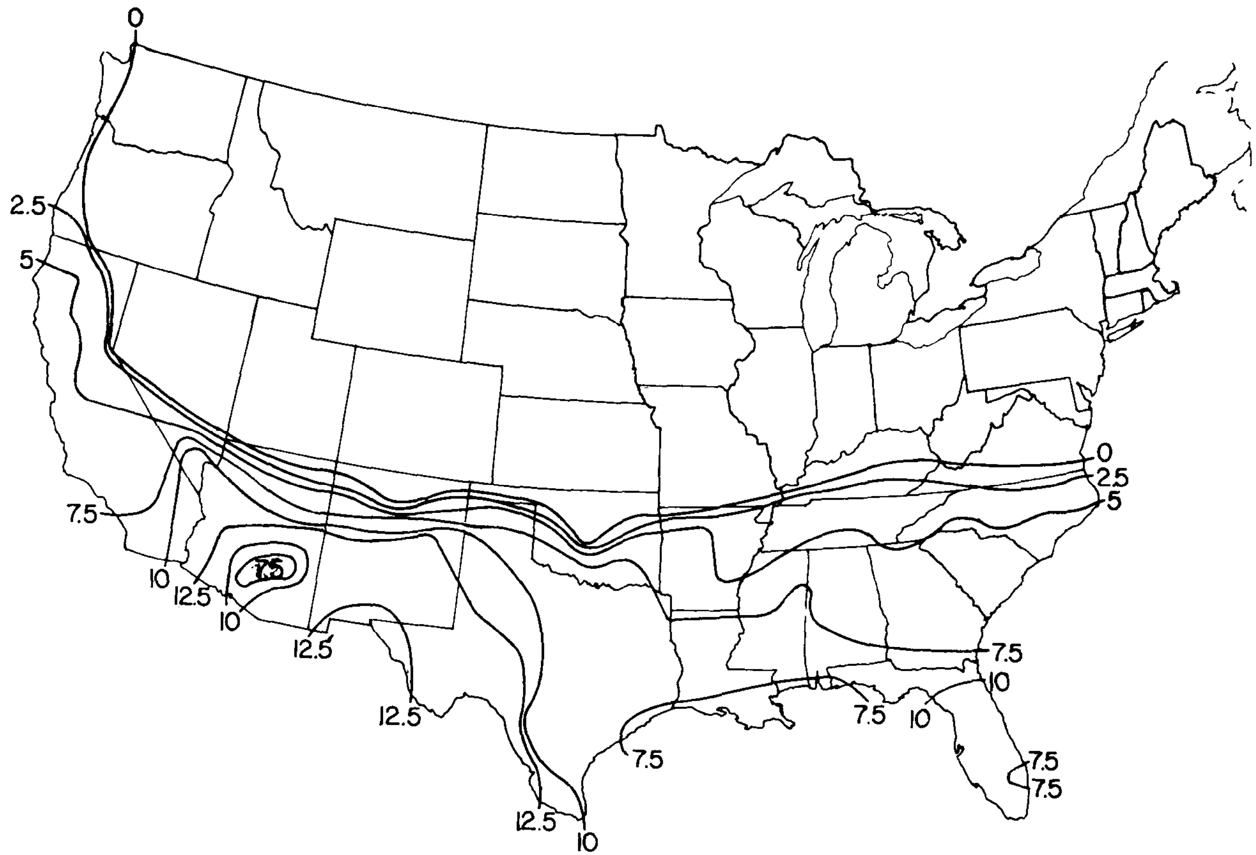

Figure 2. Average pan evaporation in cm for the continental United States for the month of February based on data taken from 1931 to 1960

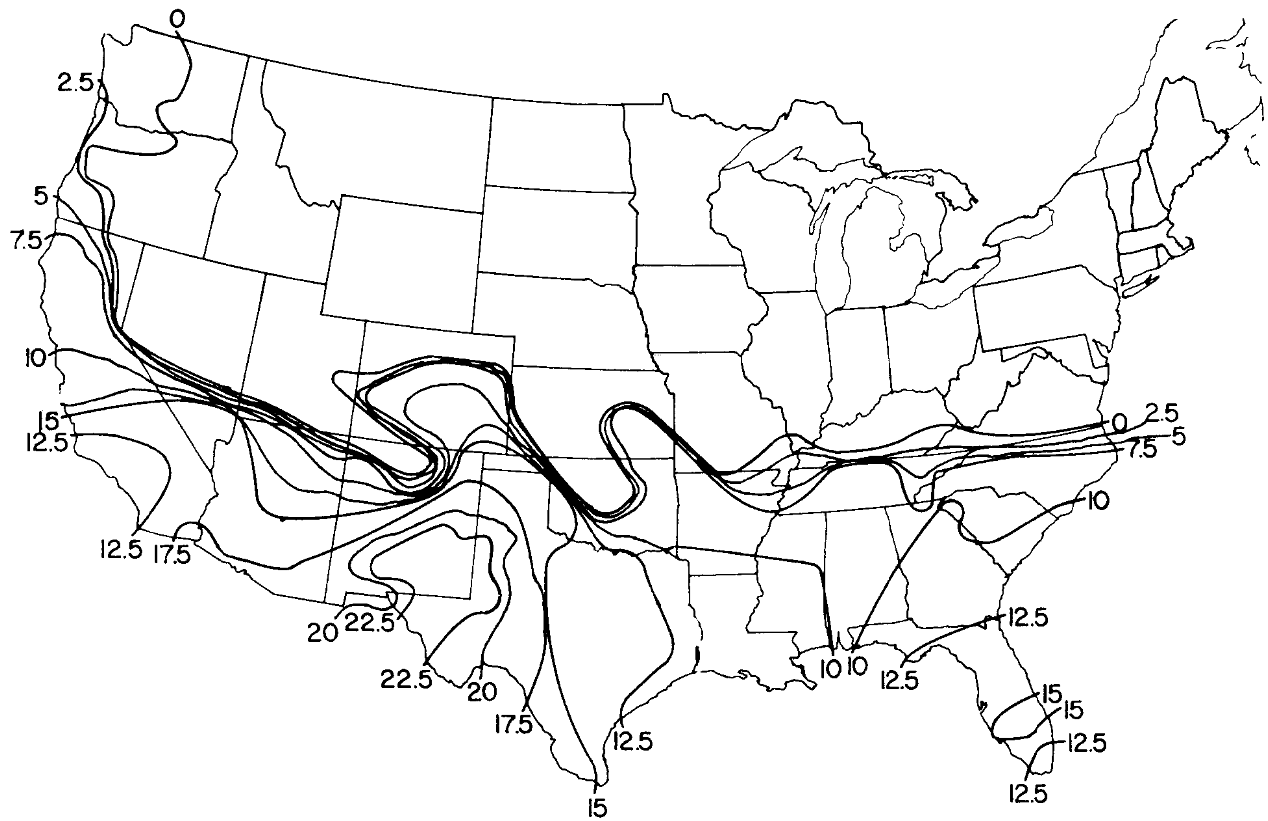

Figure 3. Average pan evaporation in cm for the continental United States for the month of March based on data taken from 1931 to 1960

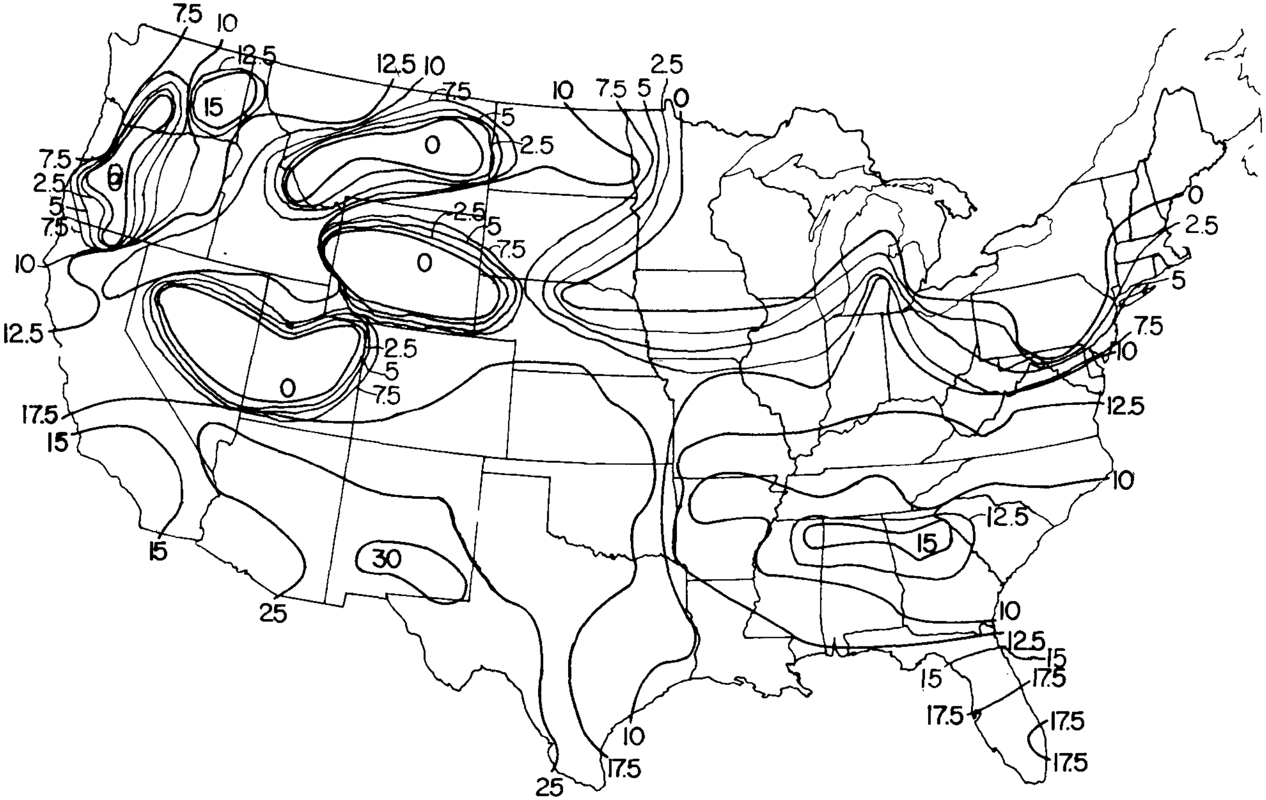

Figure 4. Average pan evaporation in cm for the continental United States for the month of April based on data taken from 1931 to 1960

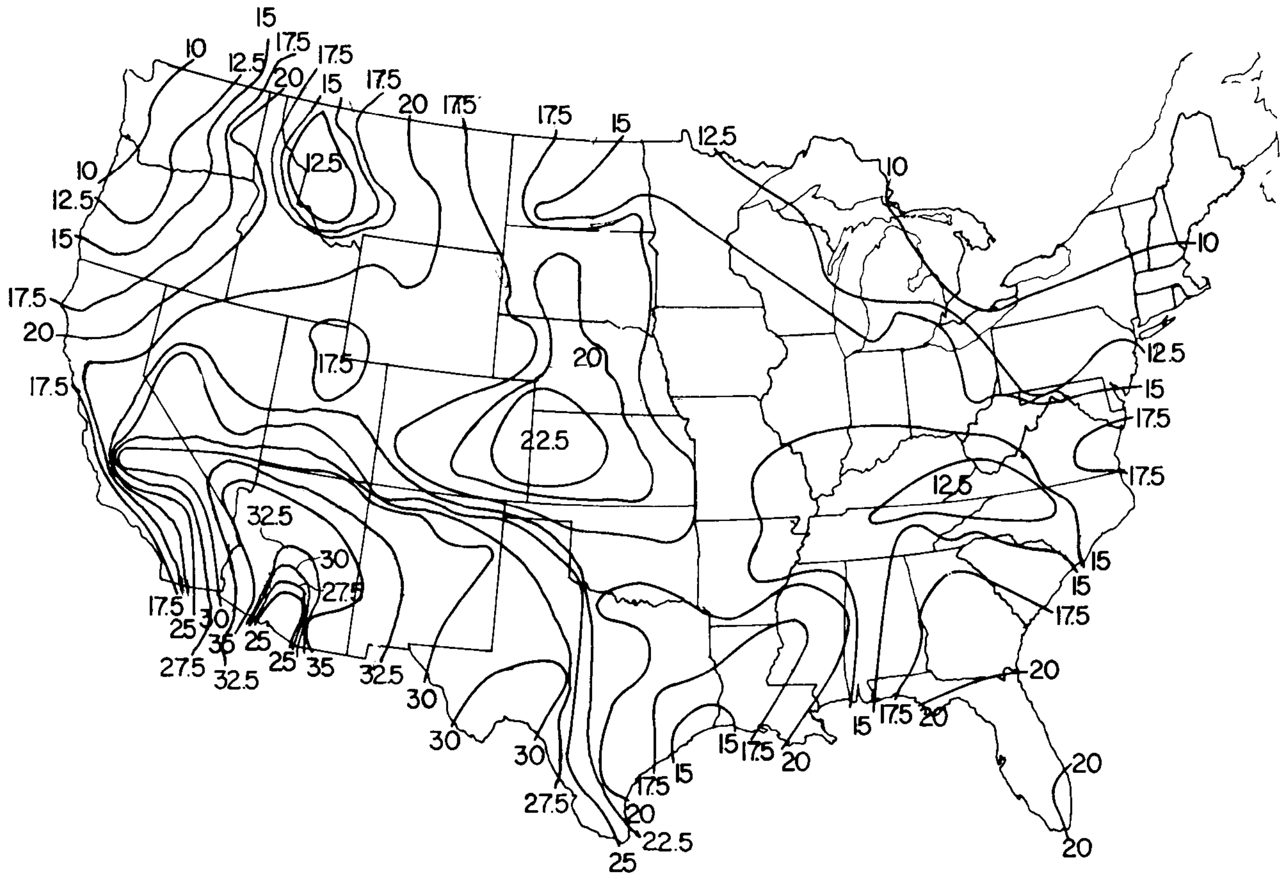

Figure 5. Average pan evaporation in cm for the continental United States for the month of May based on data taken from 1931 to 1960

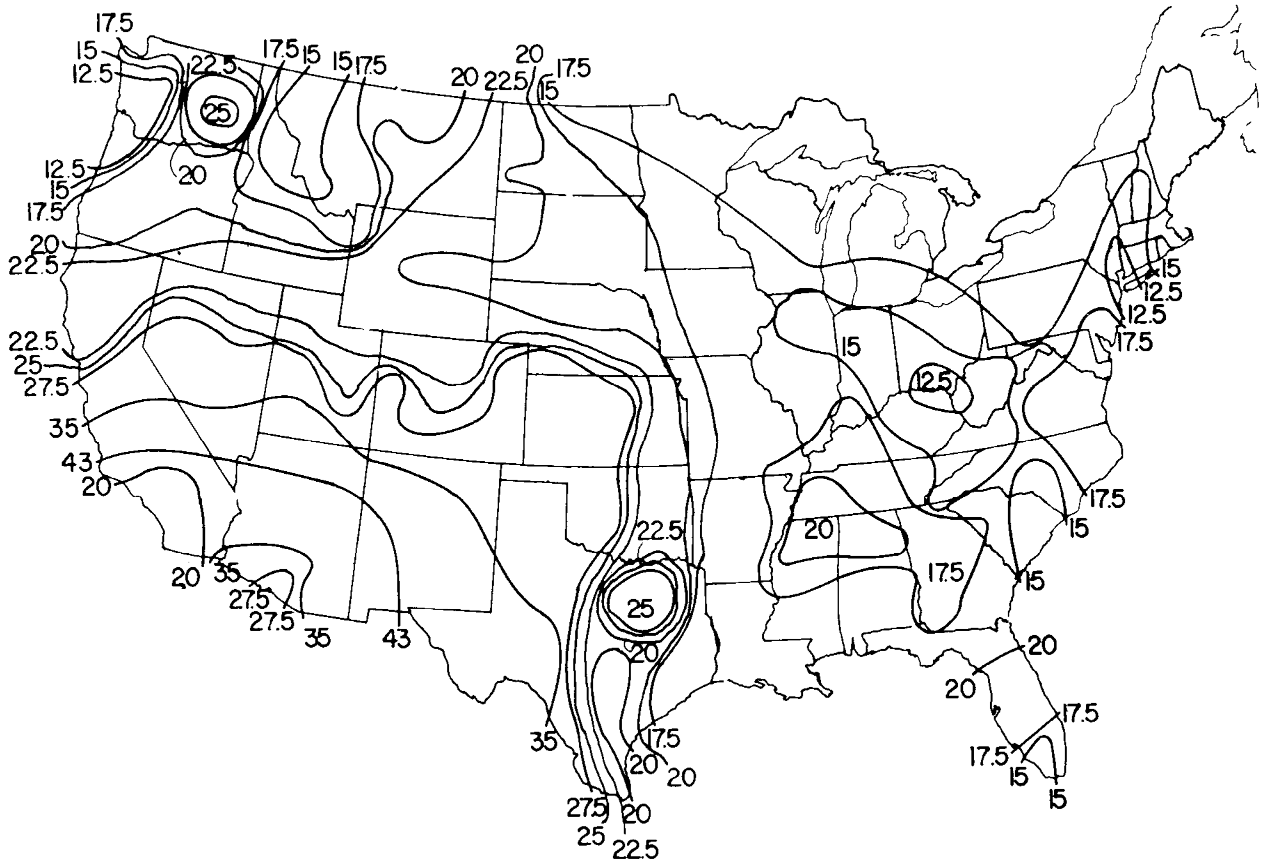

Figure 6. Average pan evaporation in cm for the continental United States for the month of June based on data taken from 1931 to 1960

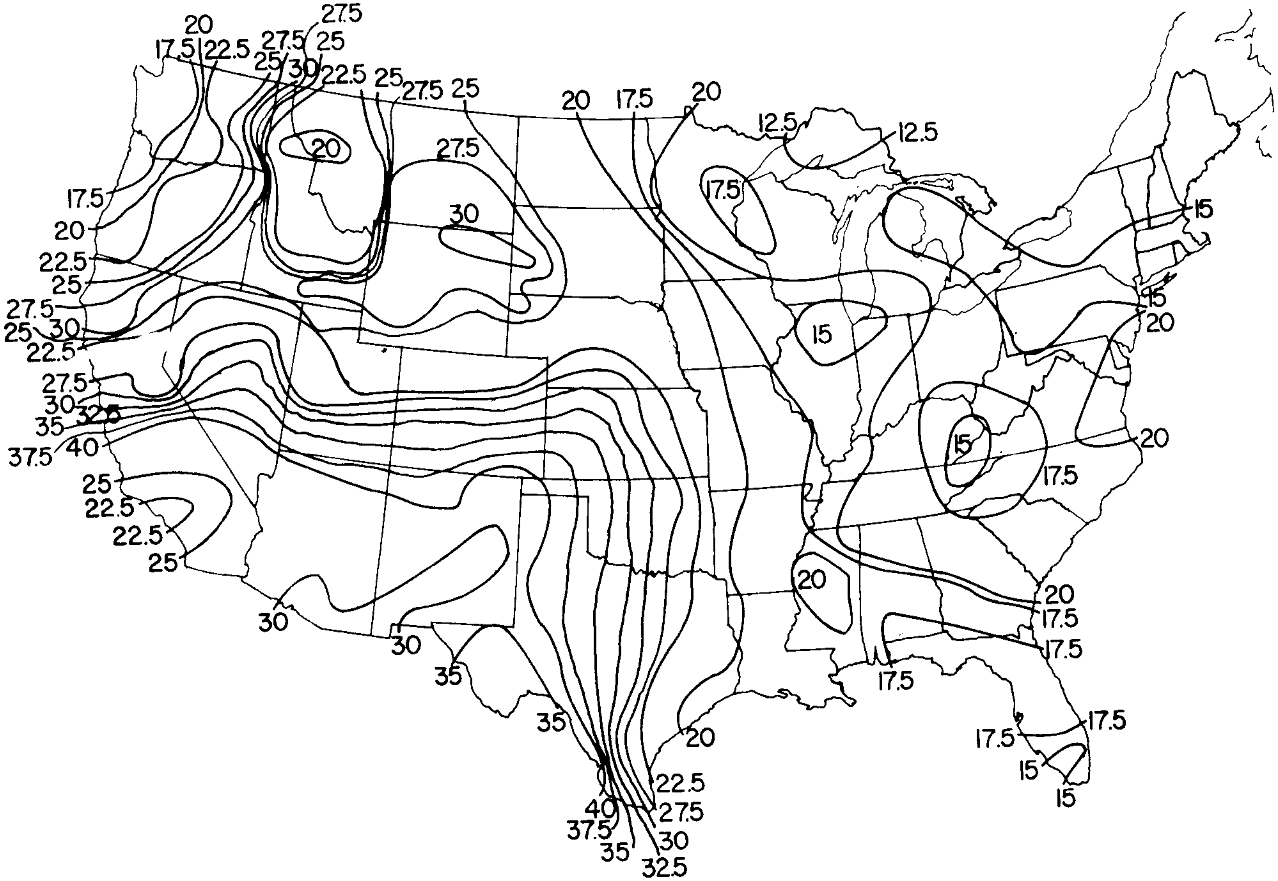

Figure 7. Average pan evaporation in cm for the continental United States for the month of July based on data taken from 1931 to 1960

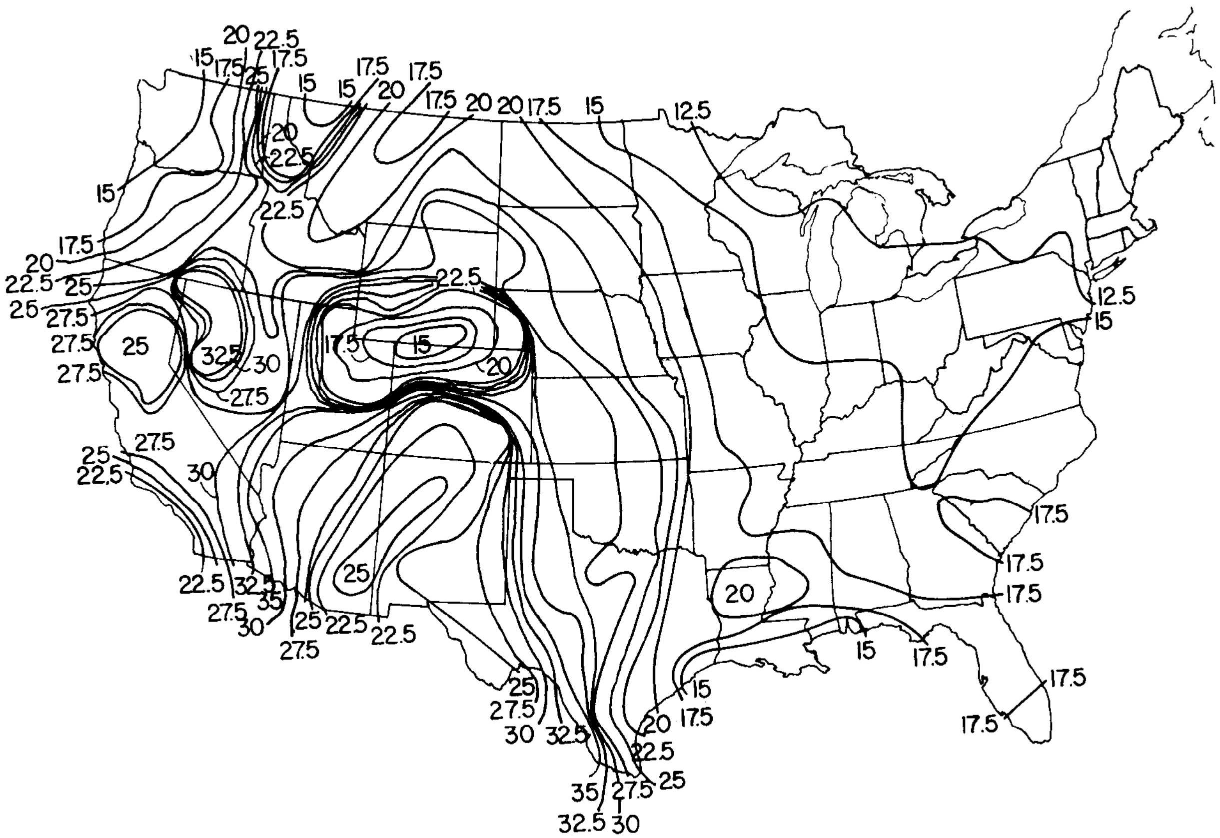

Figure 8. Average pan evaporation in cm for the continental United States for the month of August based on data taken from 1931 to 1960

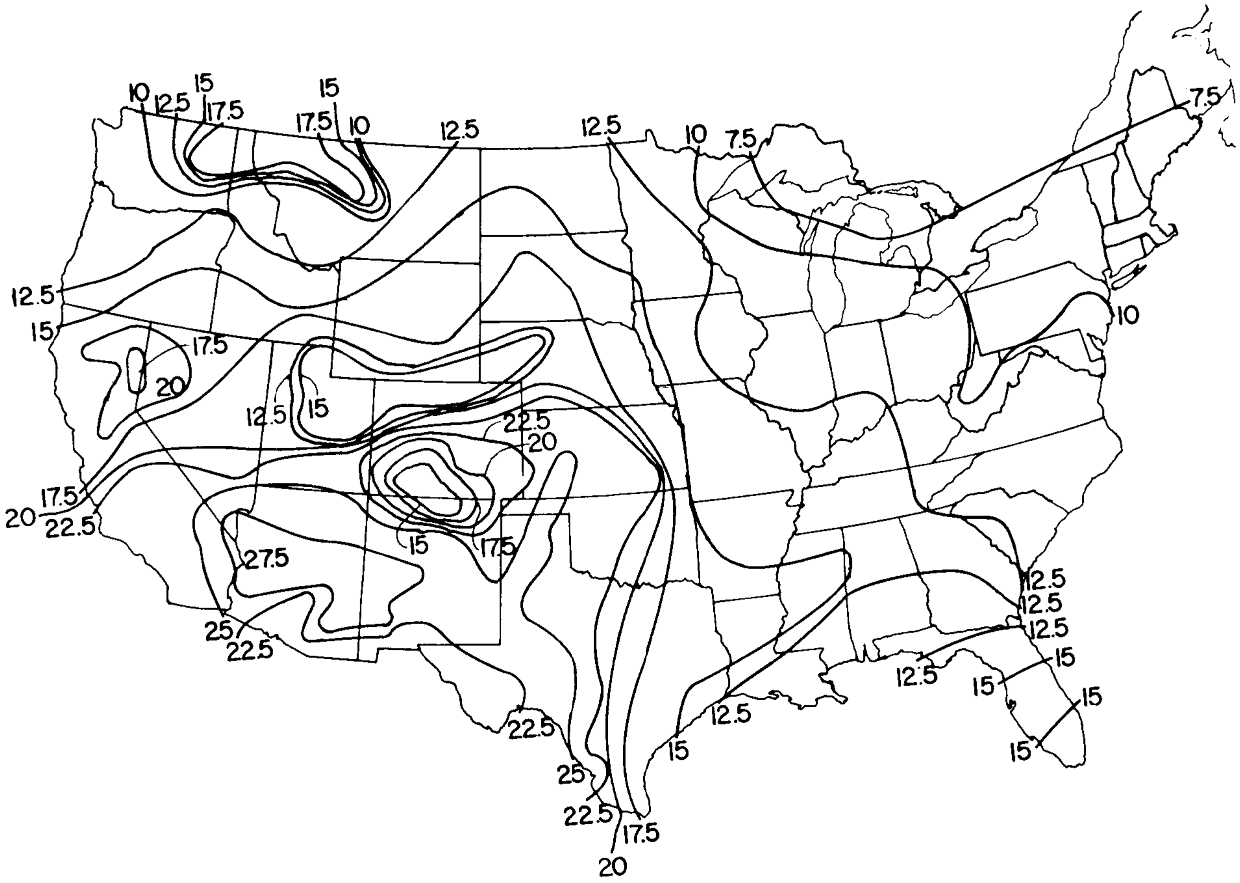

Figure 9. Average pan evaporation in cm for the continental United States for the month of September based on data taken from 1931 to 1960

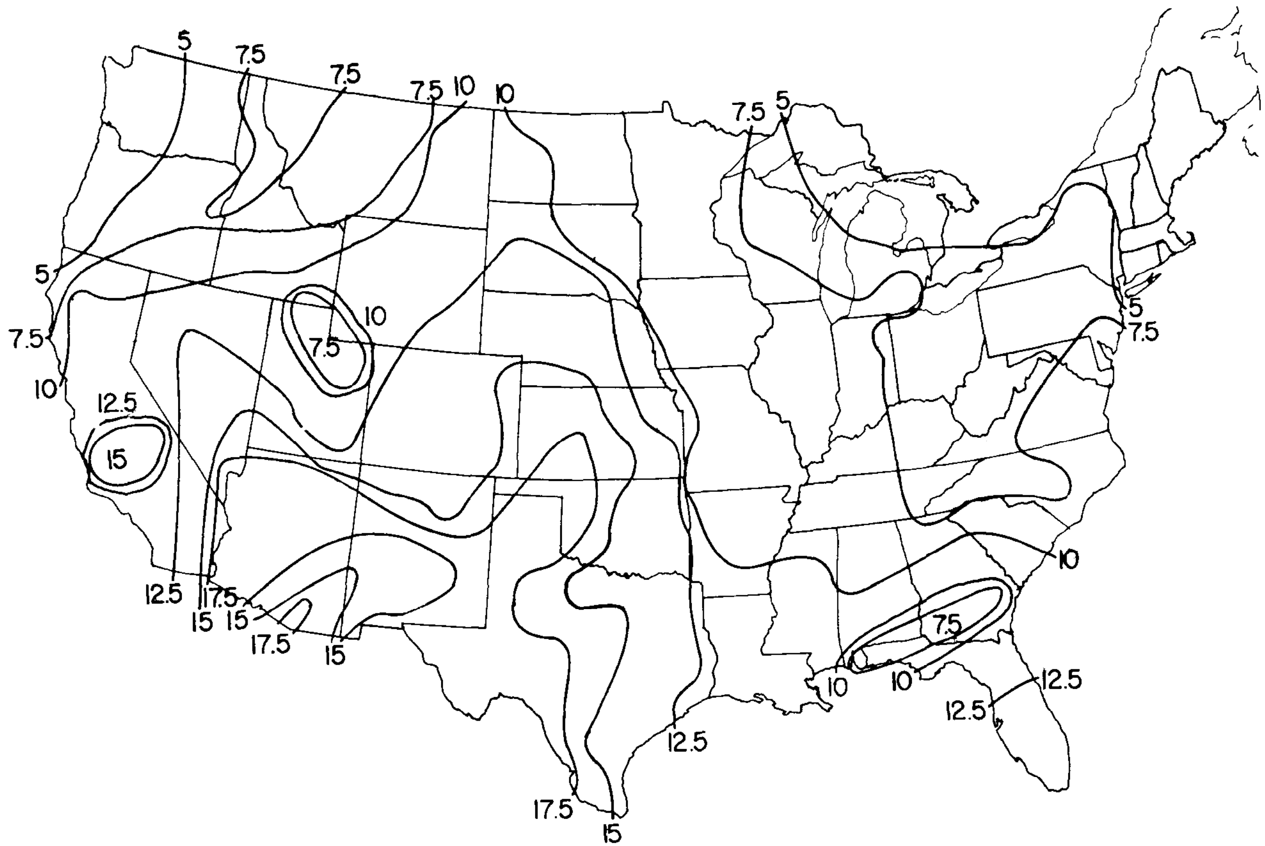

Figure 10. Average pan evaporation in cm for the continental United States for the month of October based on data taken from 1931 to 1960

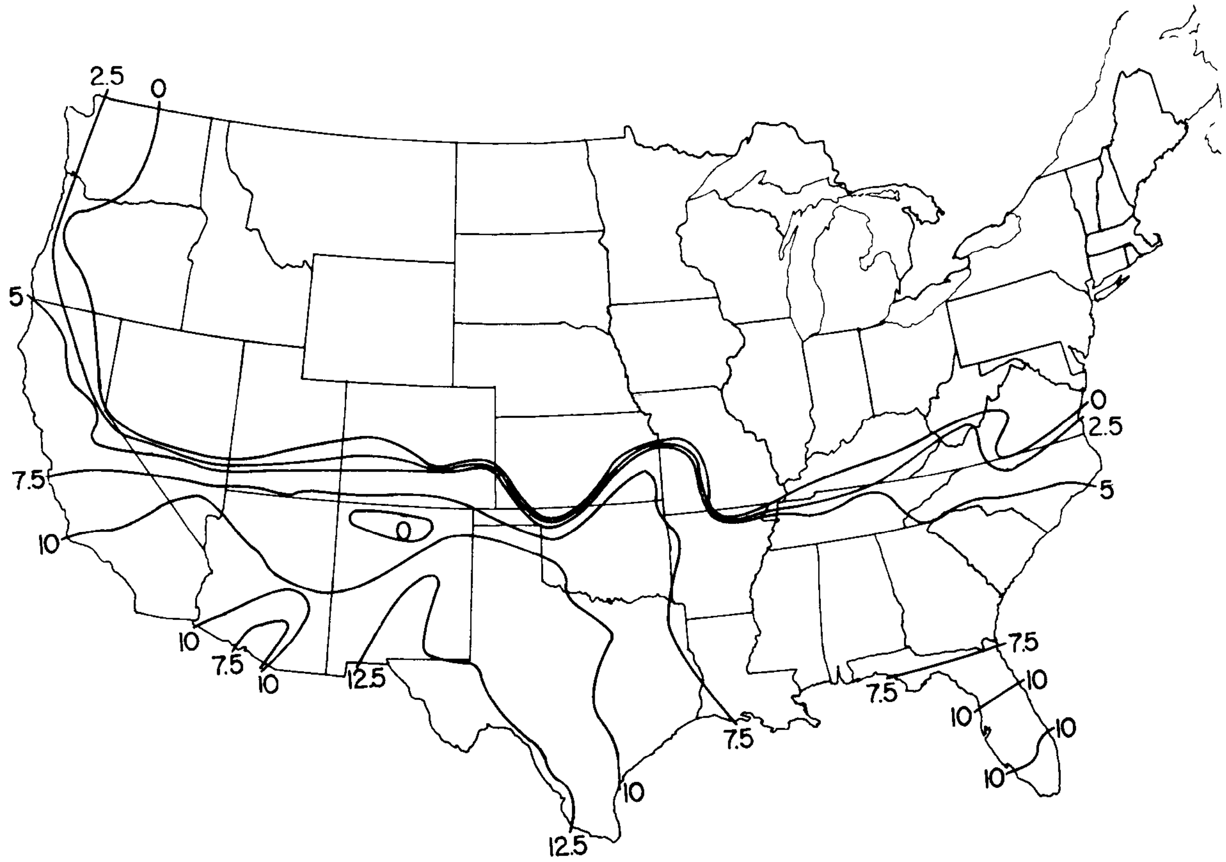

Figure 11. Average pan evaporation in cm for the continental United States for the month of November based on data taken from 1931 to 1960

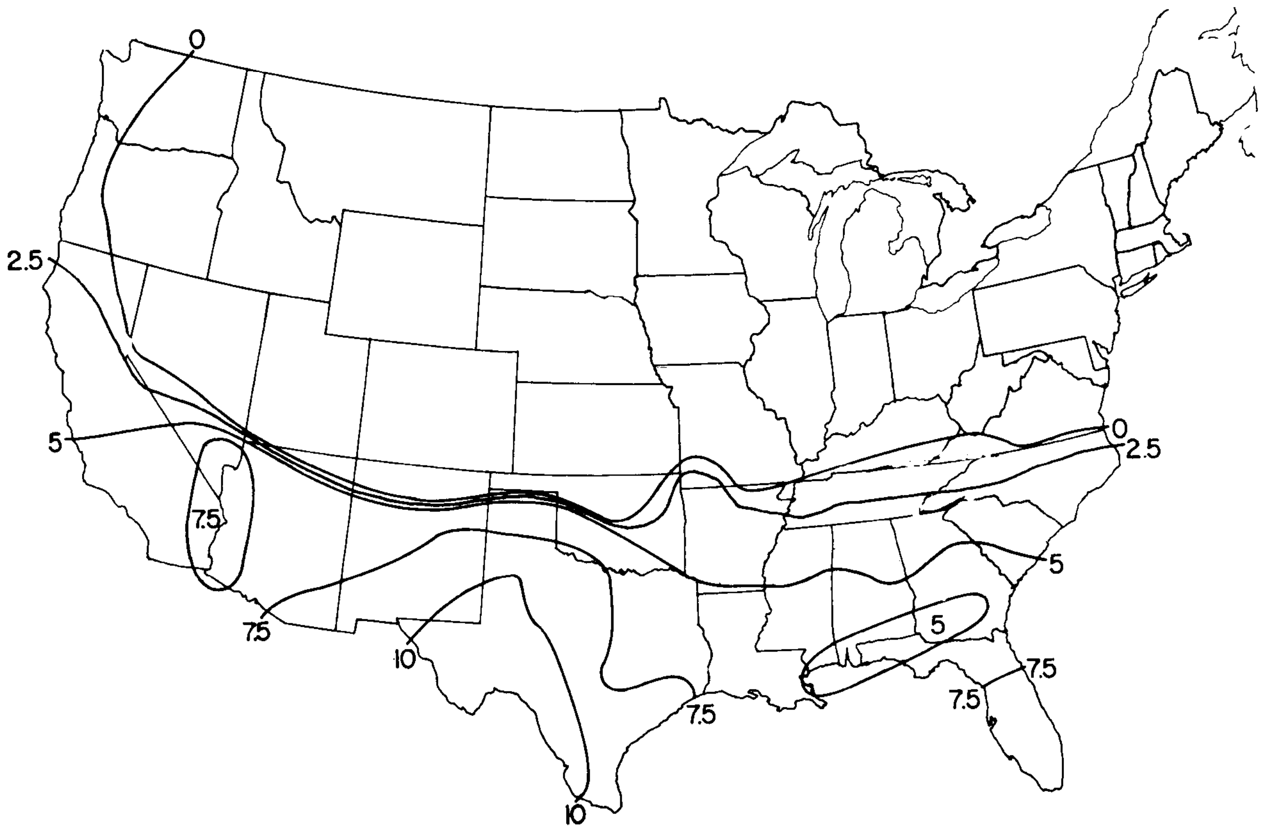

Figure 12. Average pan evaporation in cm for the continental United States for the month of December based on data taken from 1931 to 1960

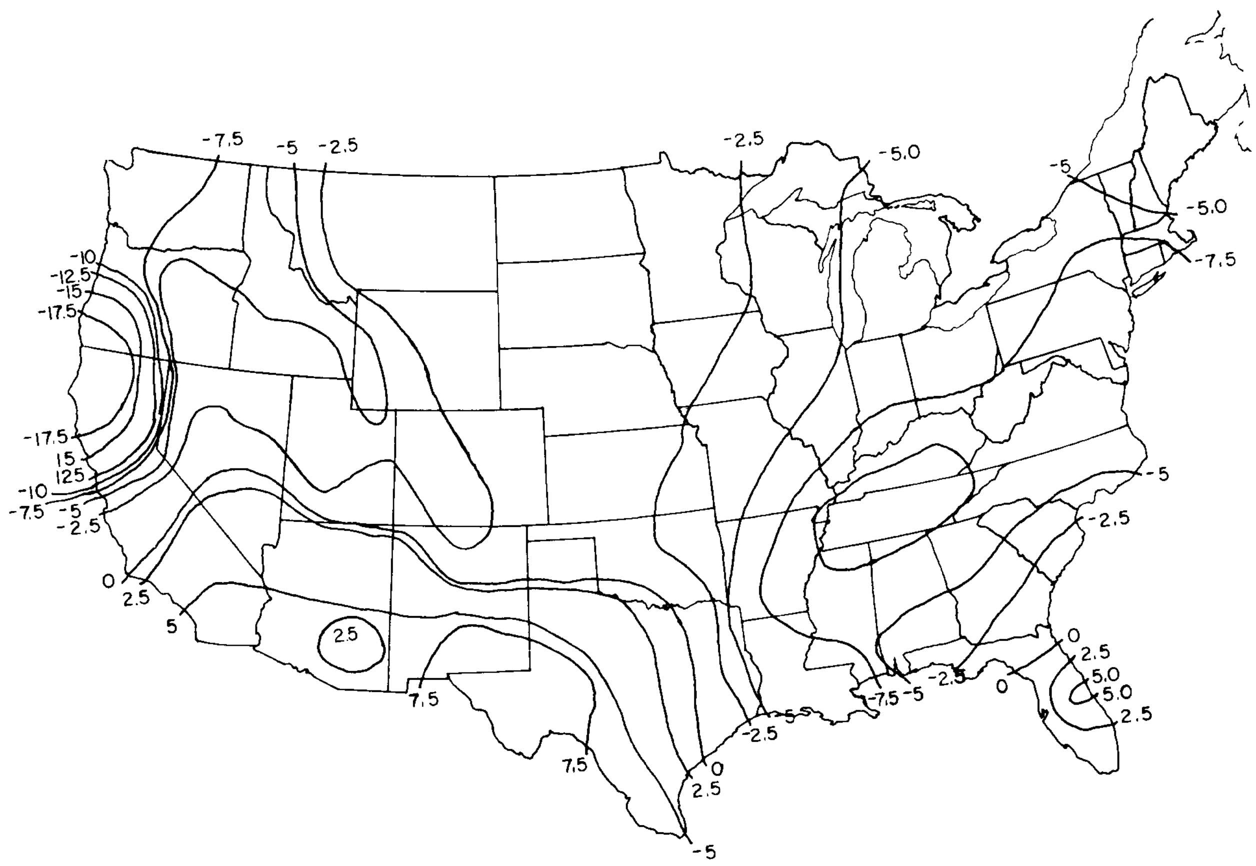

Figure 13. Average net evaporation in cm for the continental United States for the month of January based on data taken from 1931 to 1960

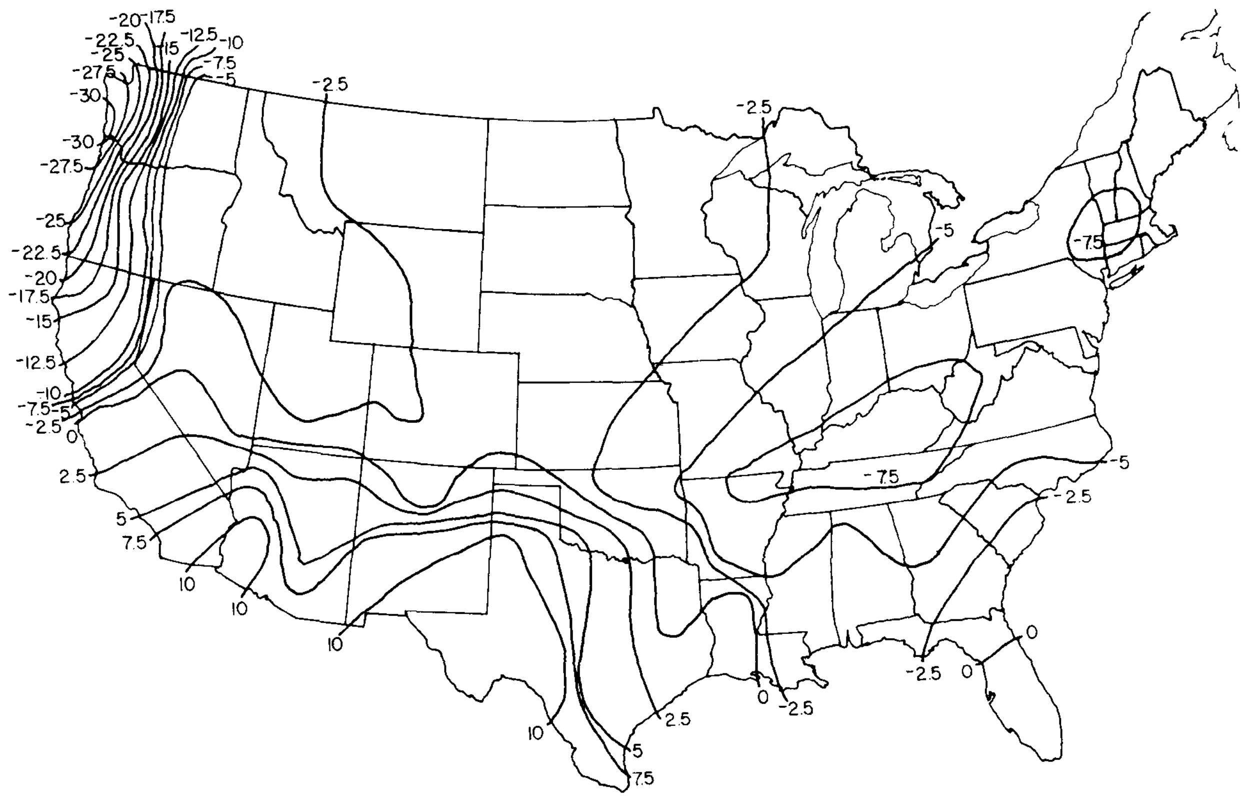

Figure 14. Average net evaporation in cm for the continental United States for the month of February based on data taken from 1931 to 1960

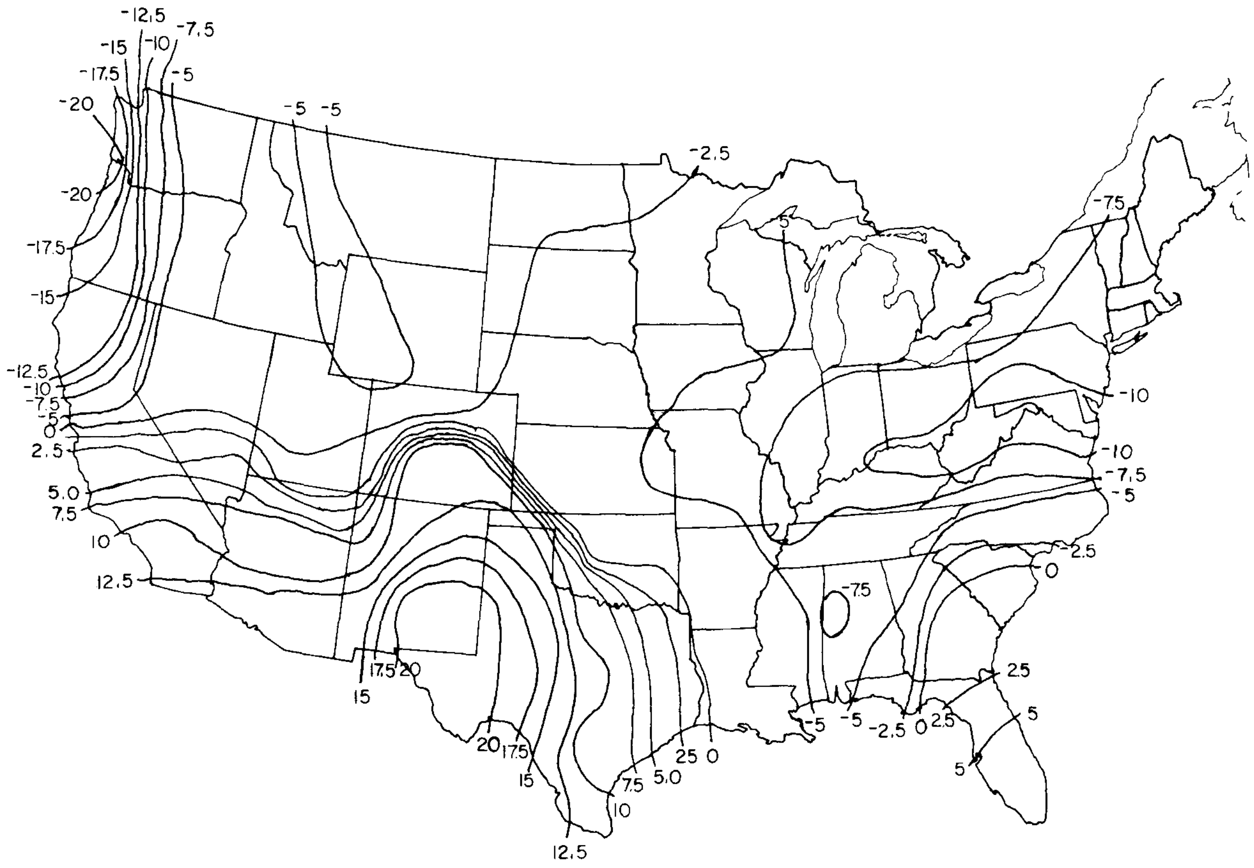

Figure 15. Average net evaporation in cm for the continental United States for the month of March based on data taken from 1931 to 1960

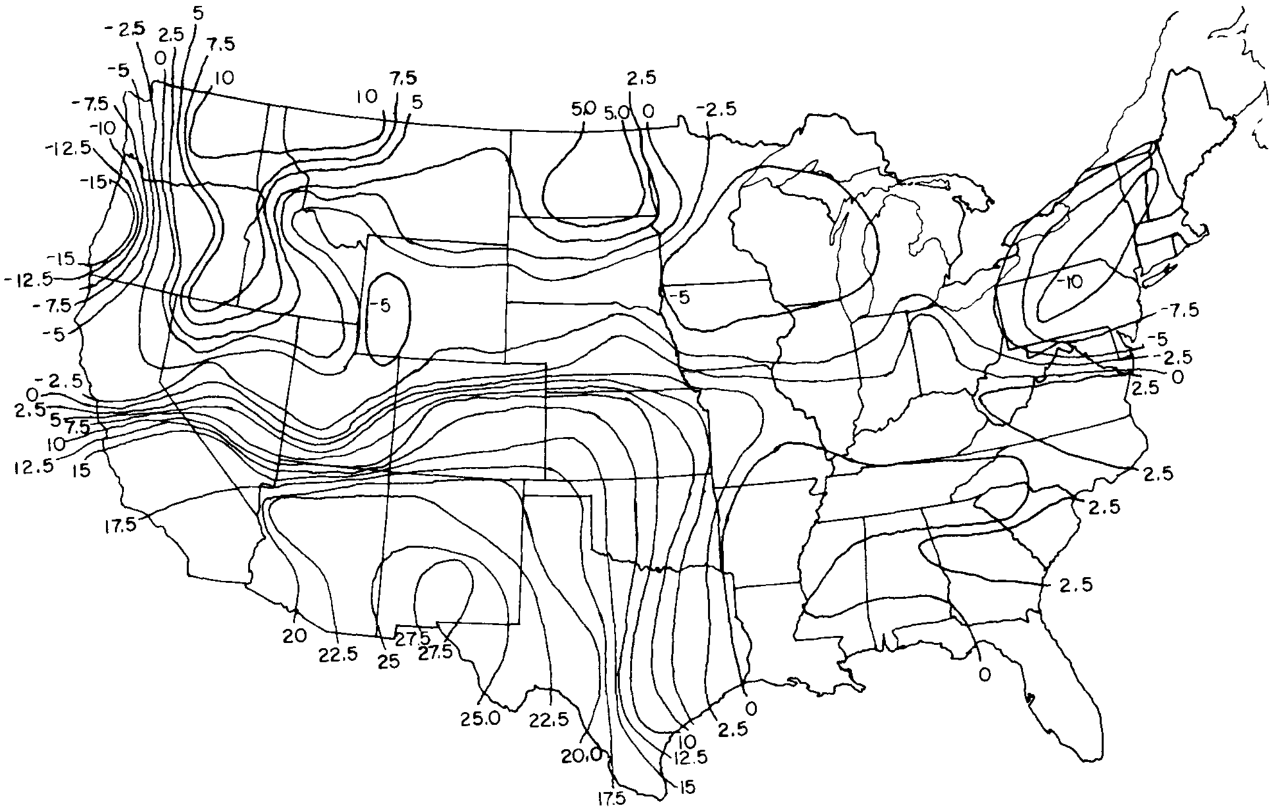

Figure 16. Average net evaporation in cm for the continental United States for the month of April based on data taken from 1931 to 1960

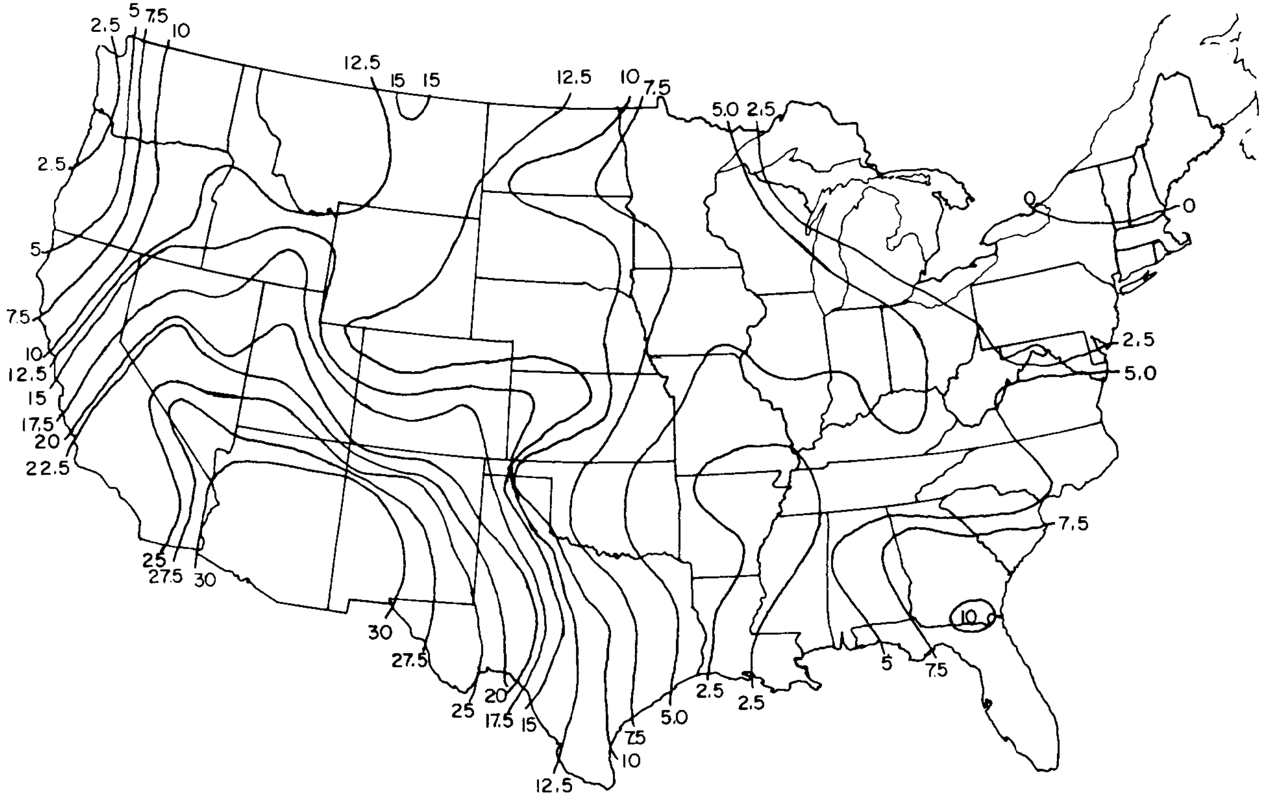

Figure 17. Average net evaporation in cm for the continental United States for the month of May based on data taken from 1931 to 1960

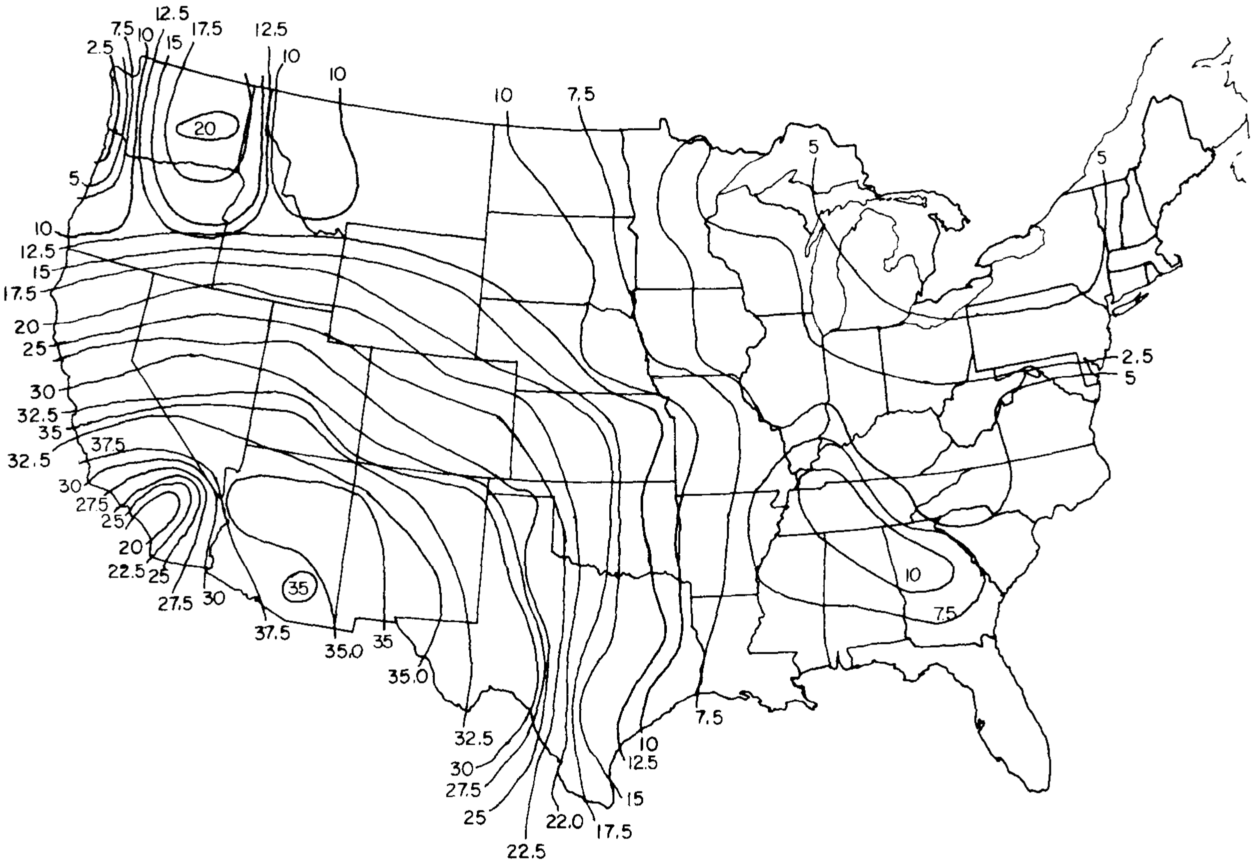

Figure 18. Average net evaporation in cm for the continental United States for the month of June based on data taken from 1931 to 1960

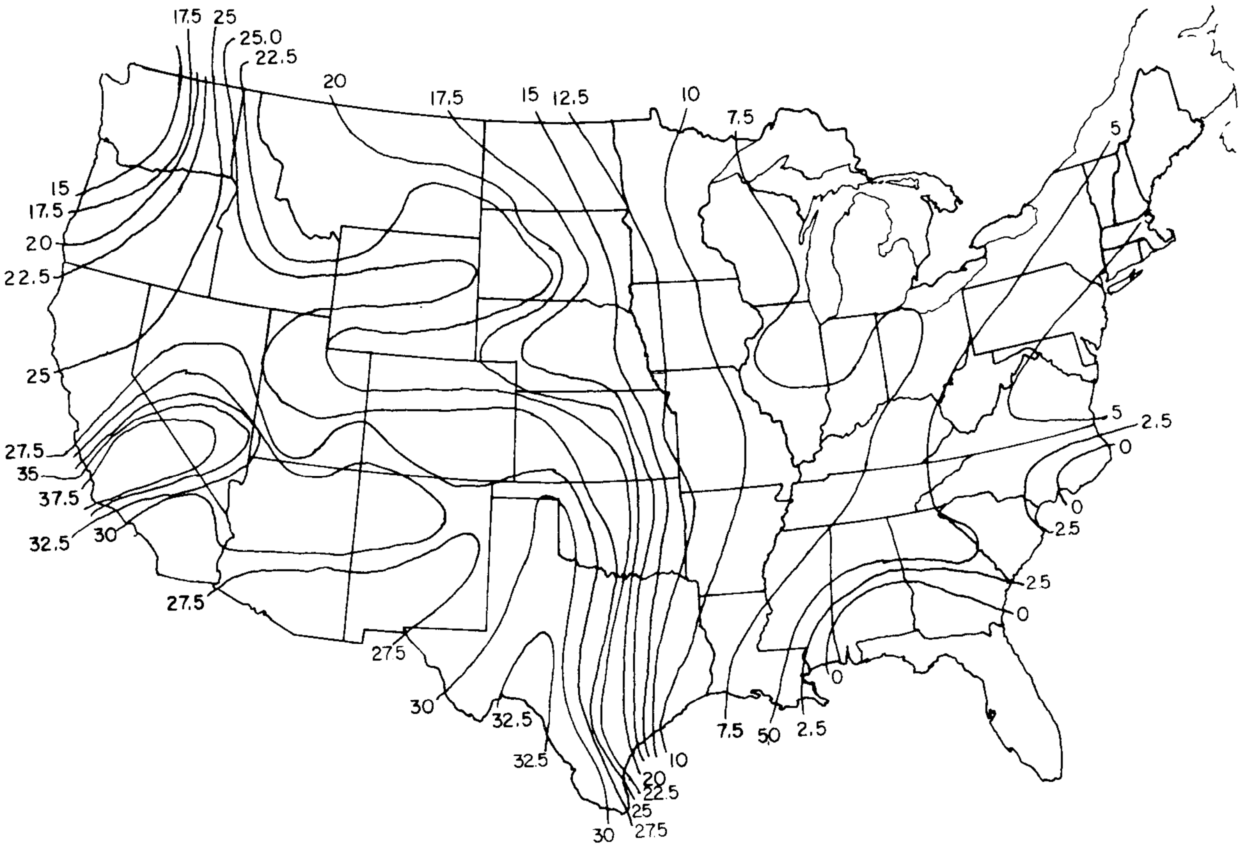

Figure 19. Average net evaporation in cm for the continental United States for the month of July based on data taken from 1931 to 1960

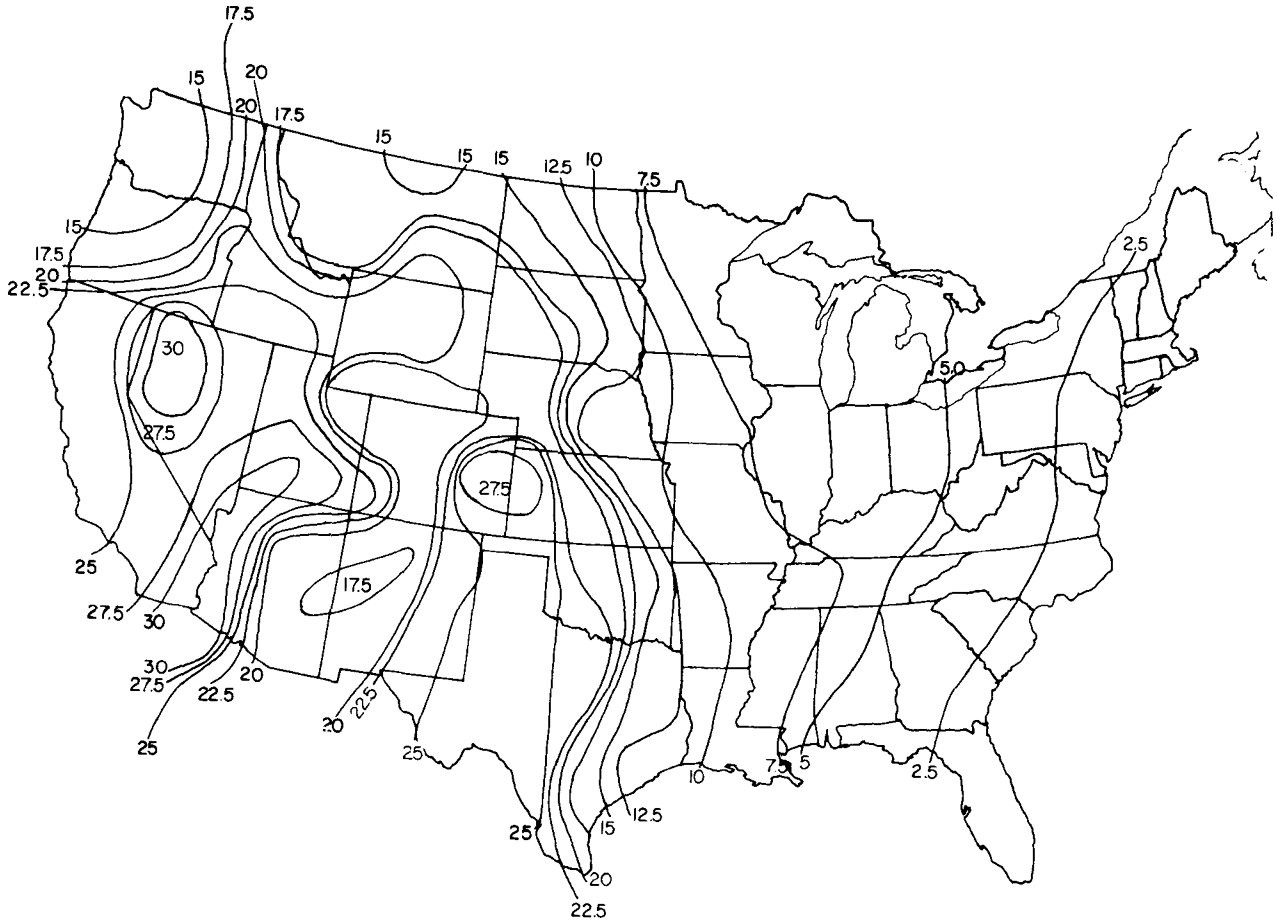

Figure 20. Average net evaporation in cm for the continental United States for the month of August based on data taken from 1931 to 1960

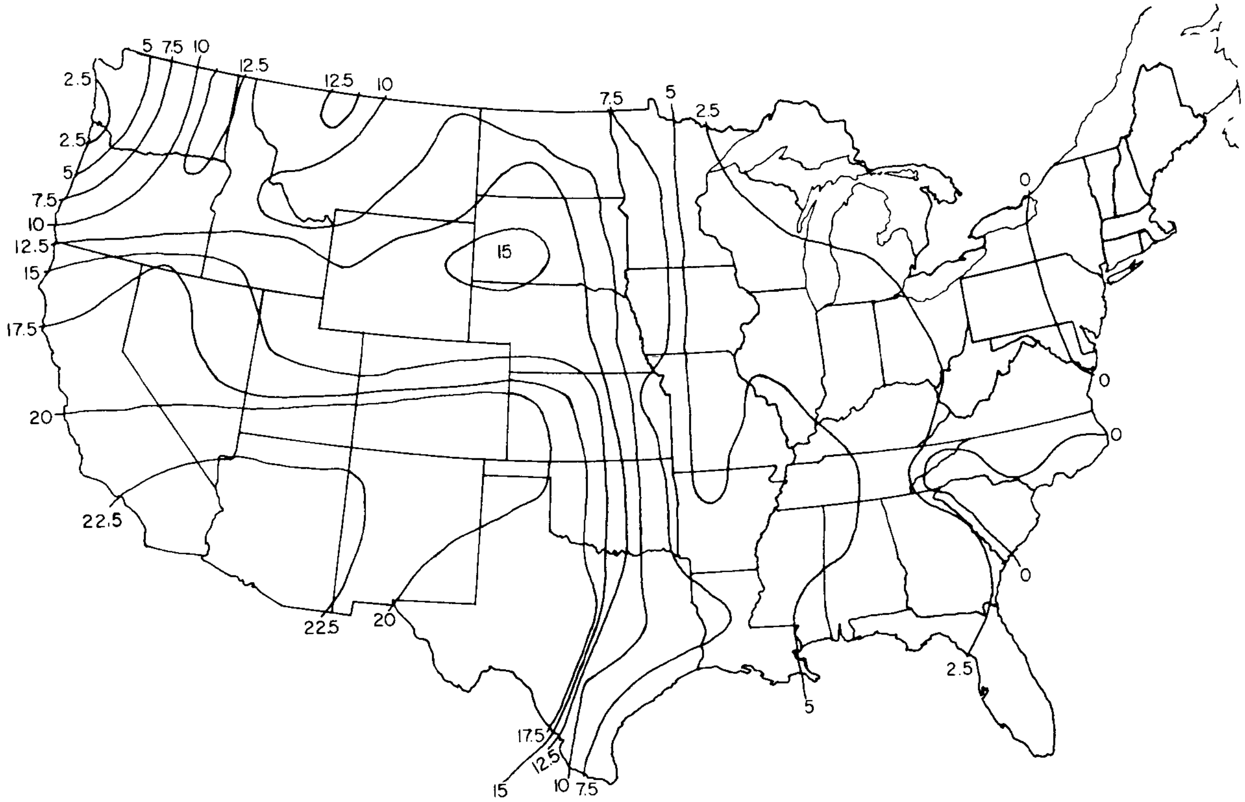

Figure 21. Average net evaporation in cm for the continental United States for the month of September based on data taken from 1931 to 1960

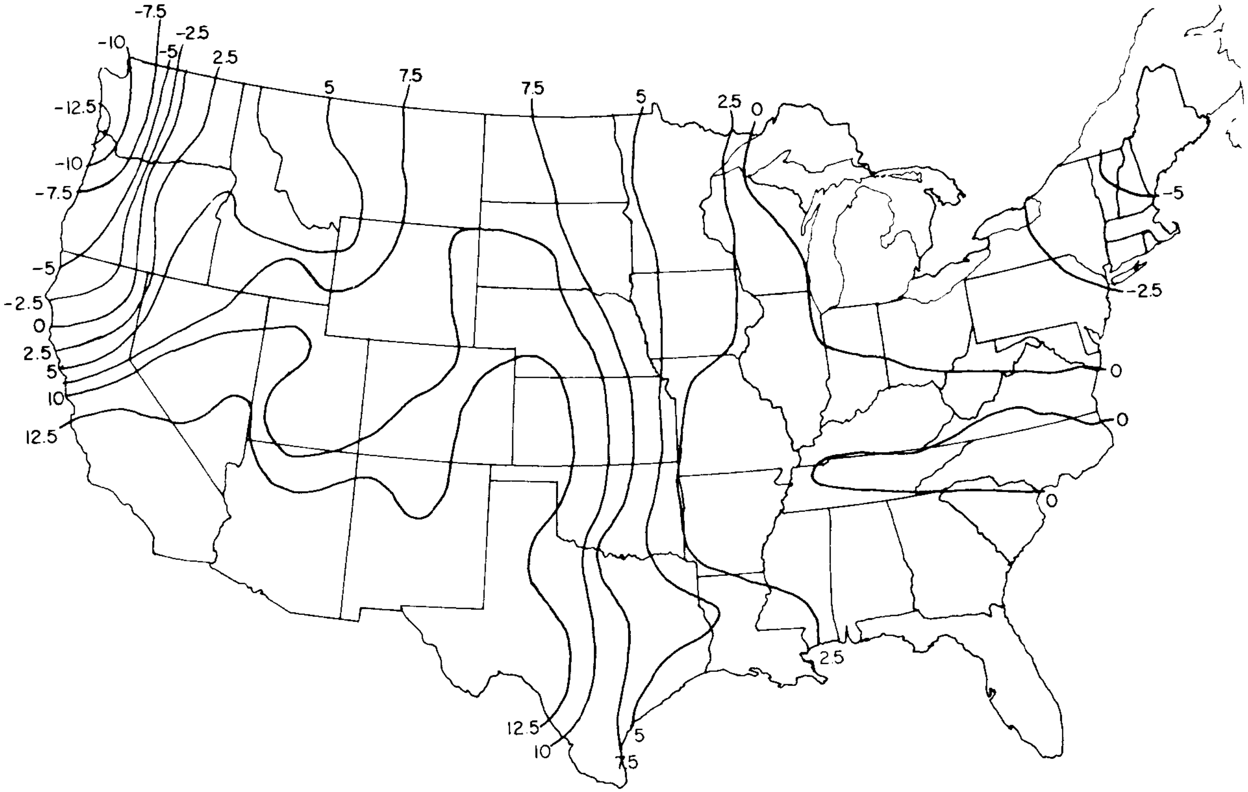

Figure 22. Average net evaporation in cm for the continental United States for the month of October based on data taken from 1931 to 1960

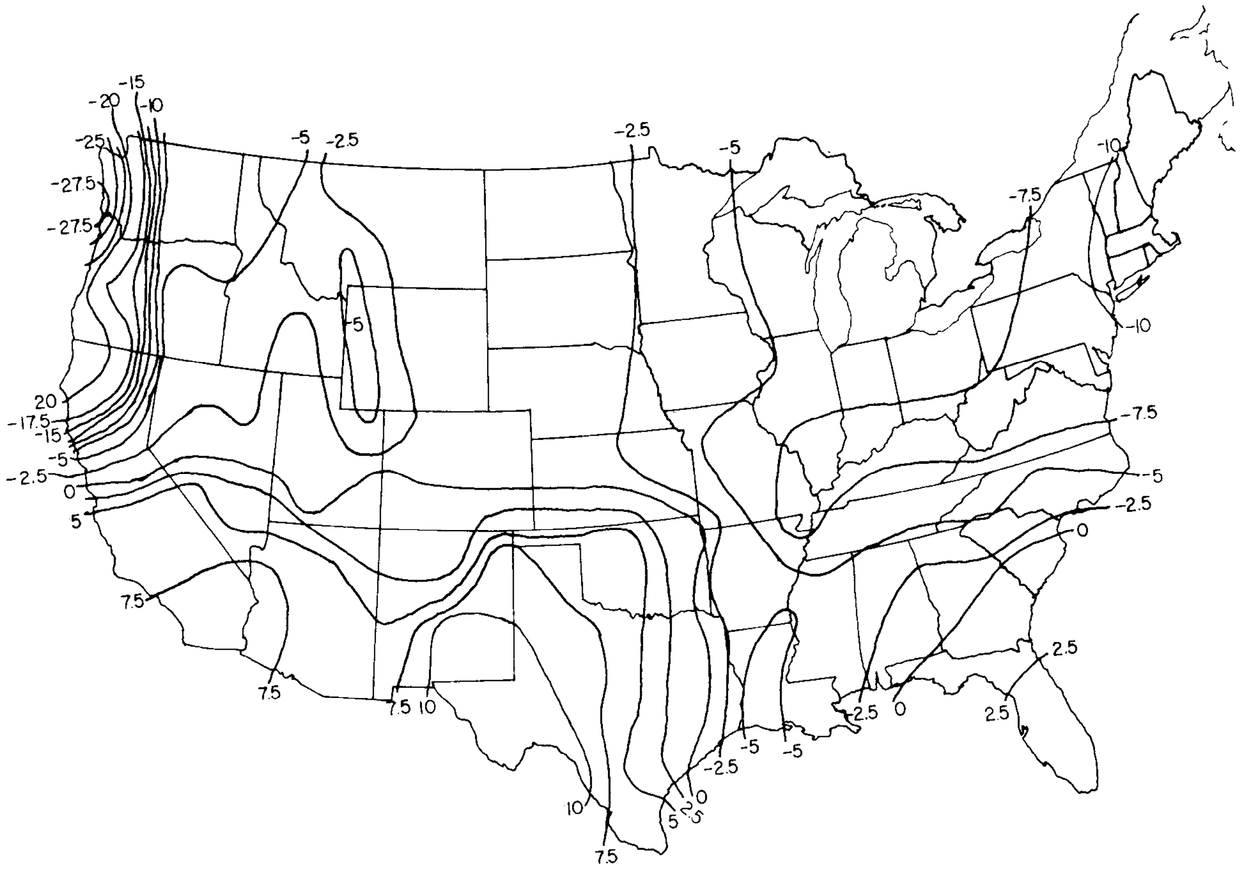

Figure 23. Average net evaporation in cm for the continental United States for the month of November based on data taken from 1931 to 1960

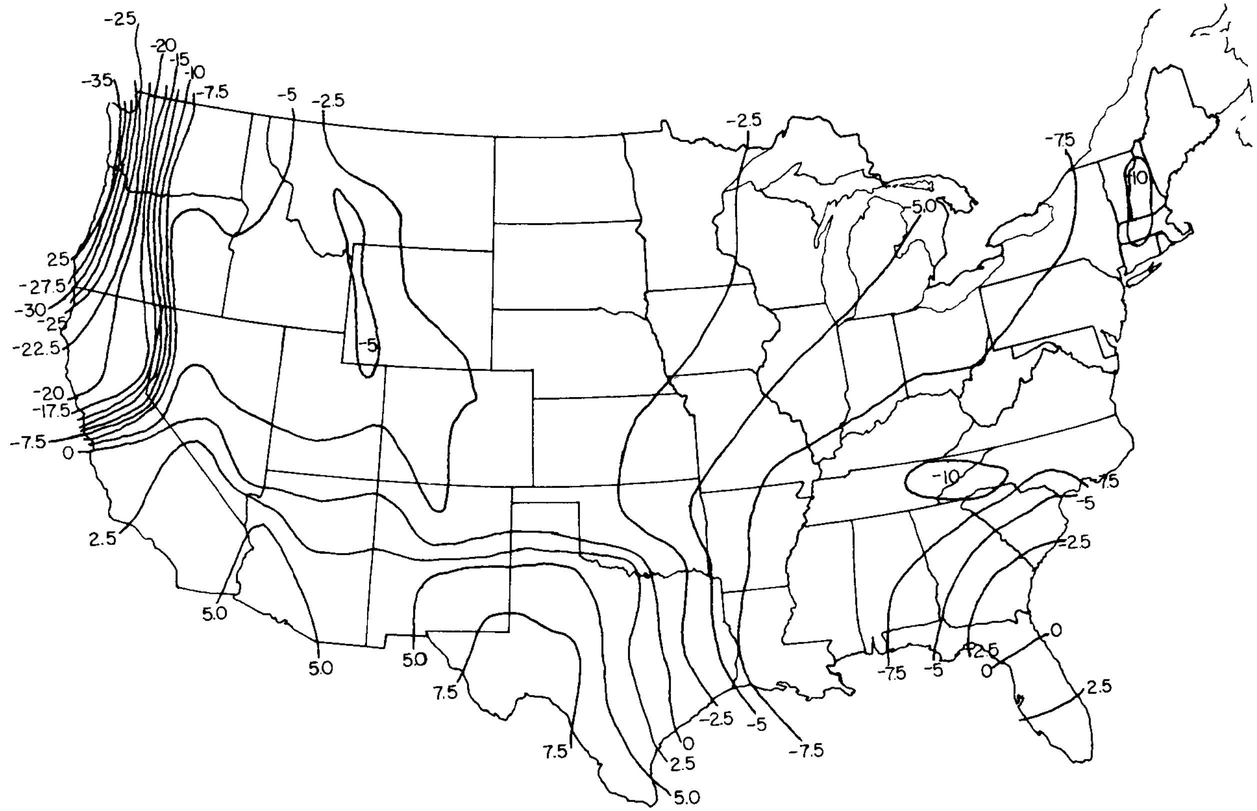

Figure 24. Average net evaporation in cm for the continental United States for the month of December based on data taken from 1931 to 1960

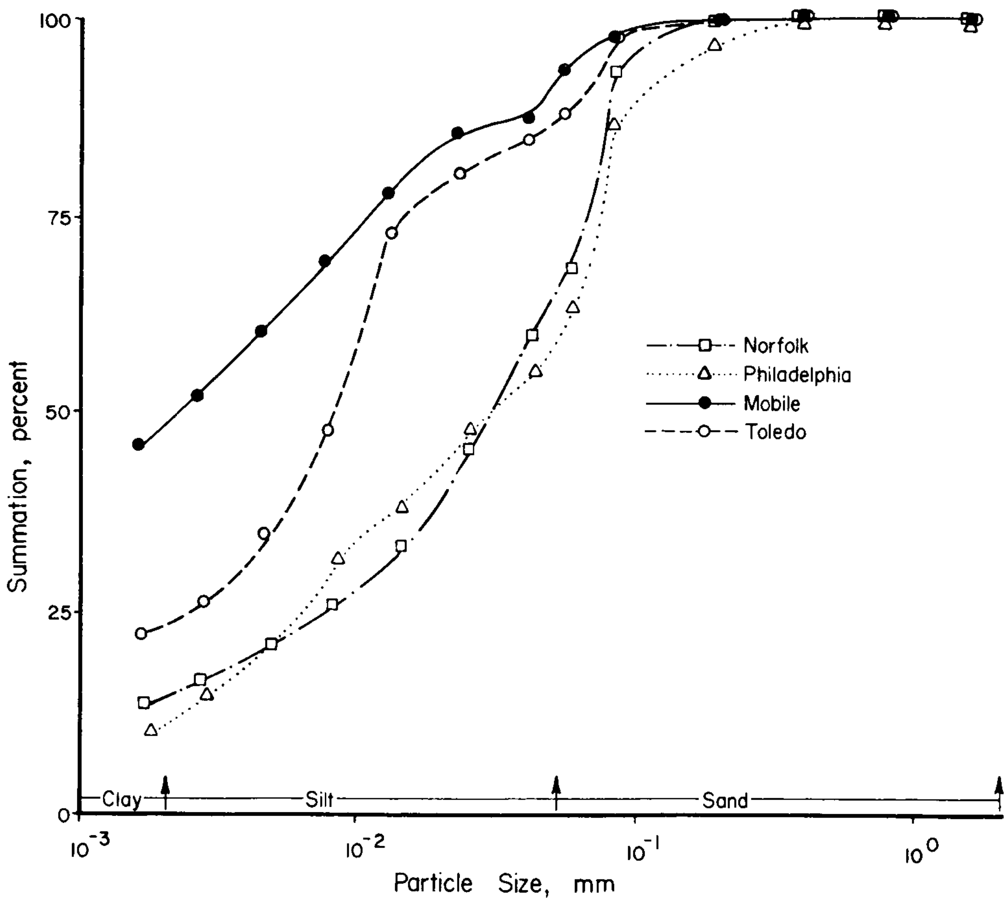

Figure 25. Particle-size distribution of the four dredged material samples

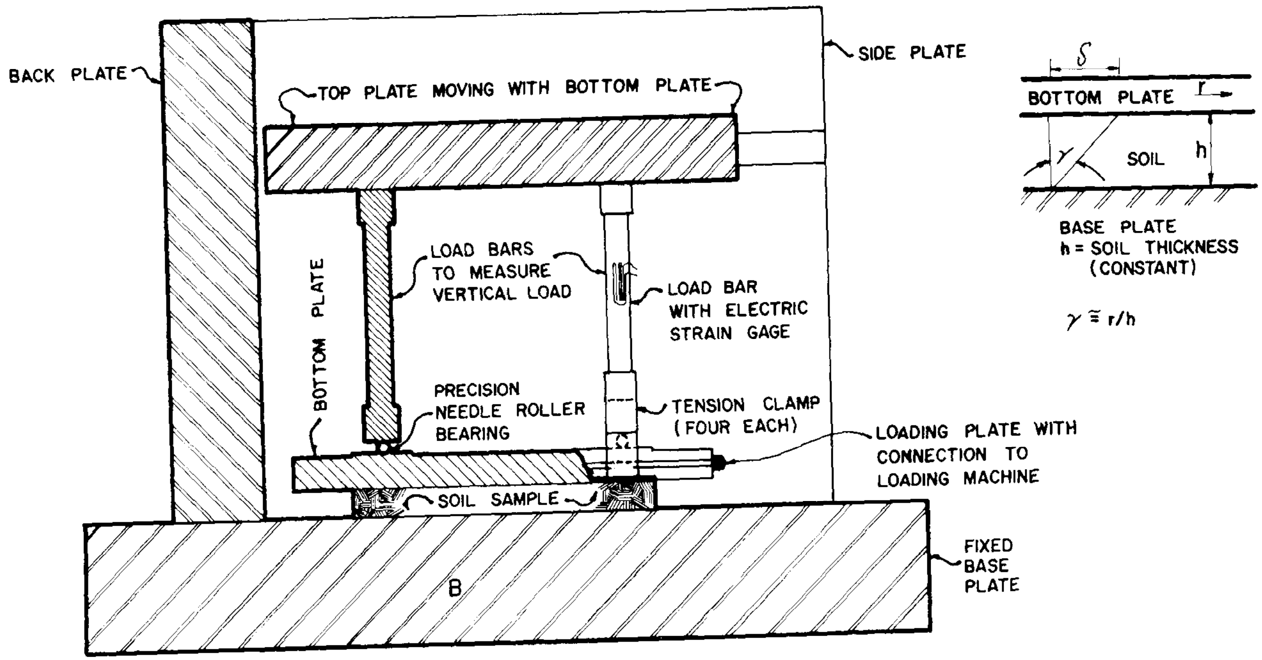

Figure 26. Schematic diagram showing a section of an assembled shear-viscometer apparatus

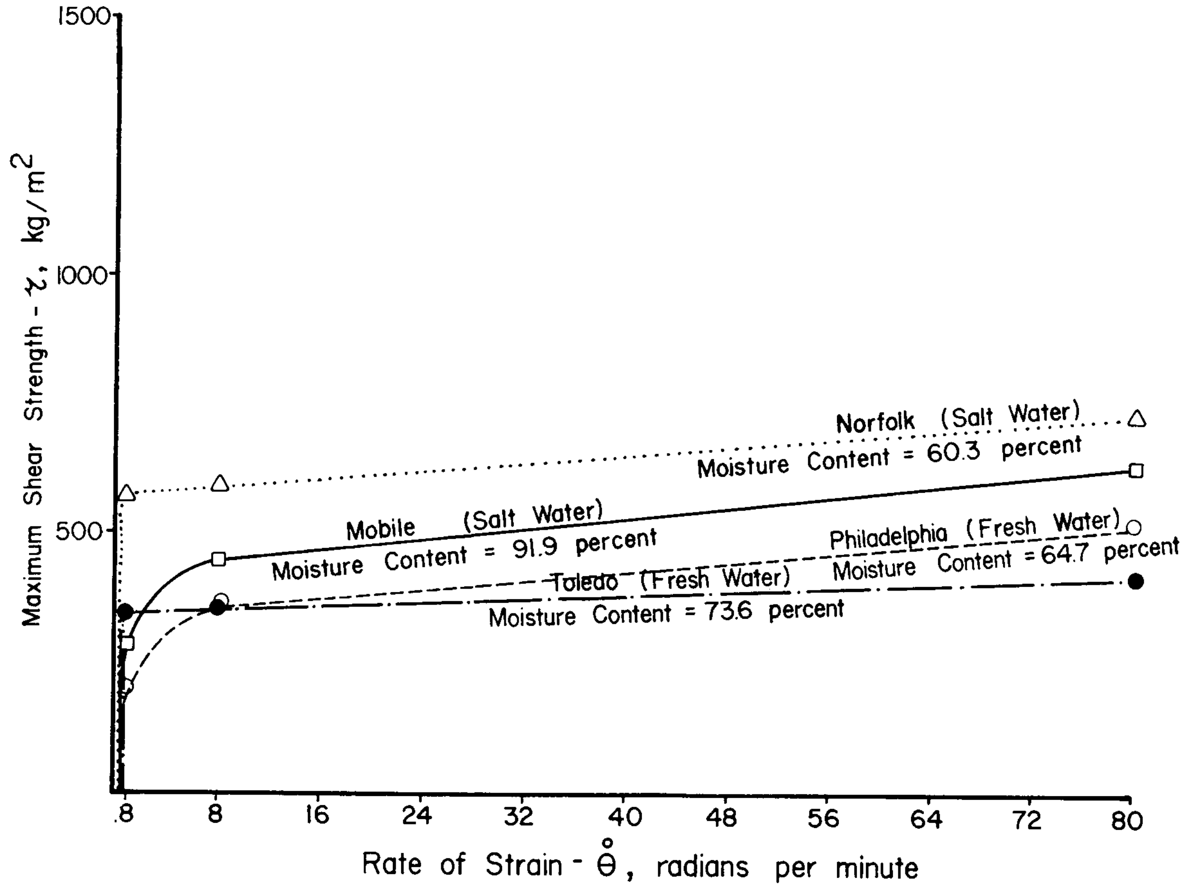

Figure 27. Shear strength as related to rate of strain in a shear-viscometer test

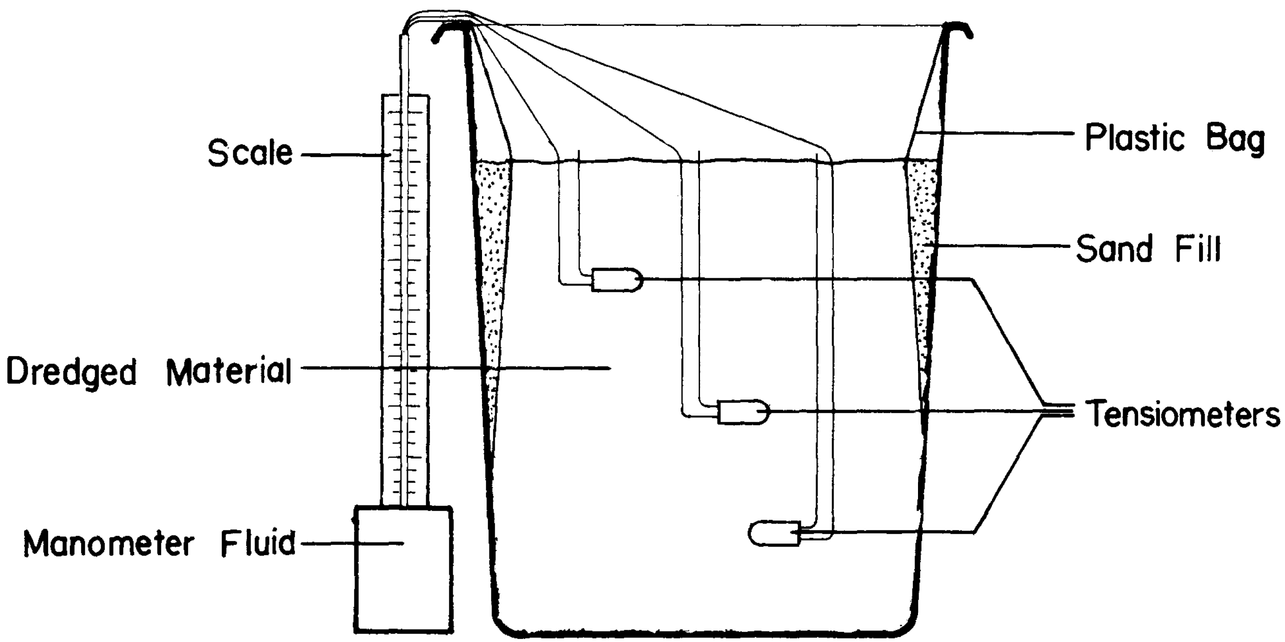

Figure 28. Schematic of container used to ensure one-dimensional moisture flow during determination of the unsaturated conductivity

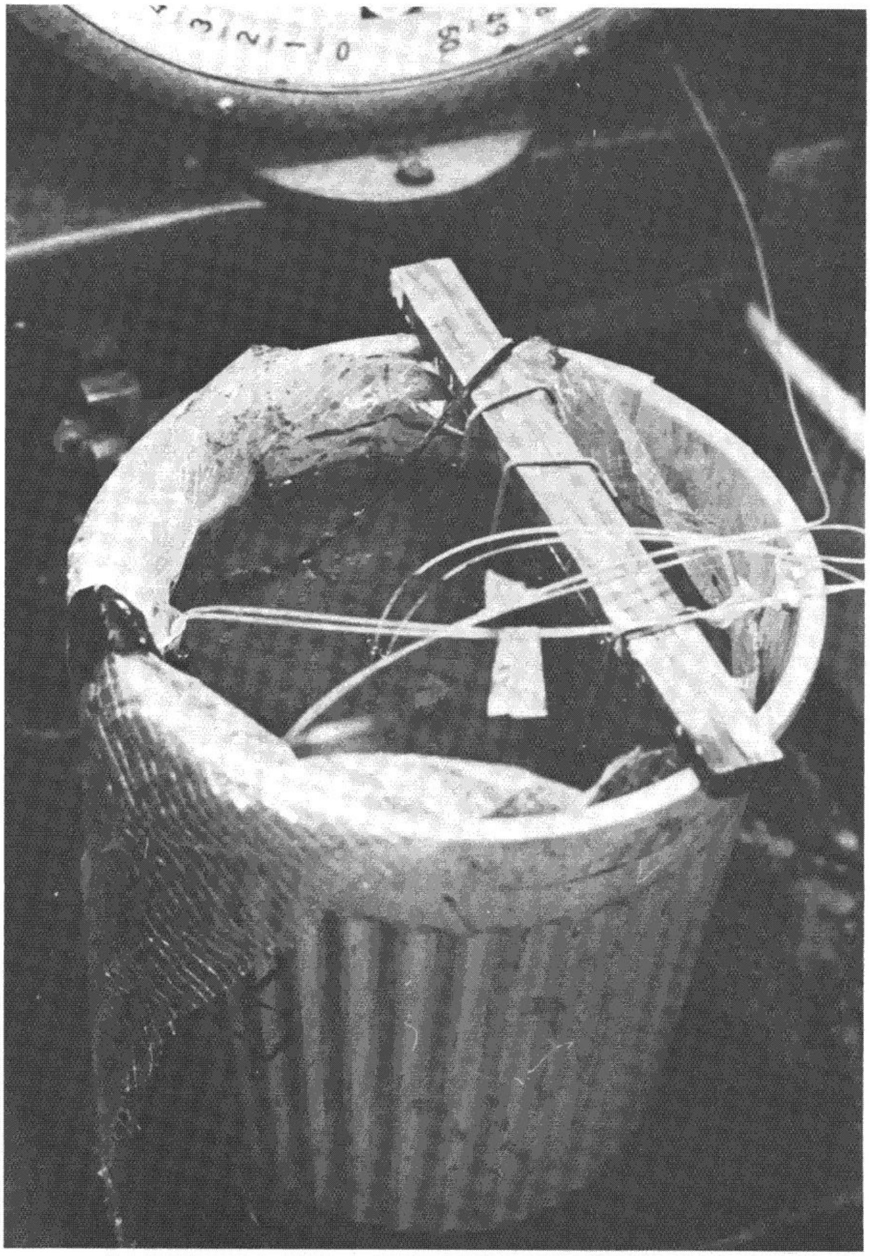

Figure 29. A container of dredged material used to determine the unsaturated conductivity shortly after filling. The wires hooked over the board were attached to the tensiometers. The board was removed shortly before the drying period was begun so that the tensiometers could move with the shrinking material

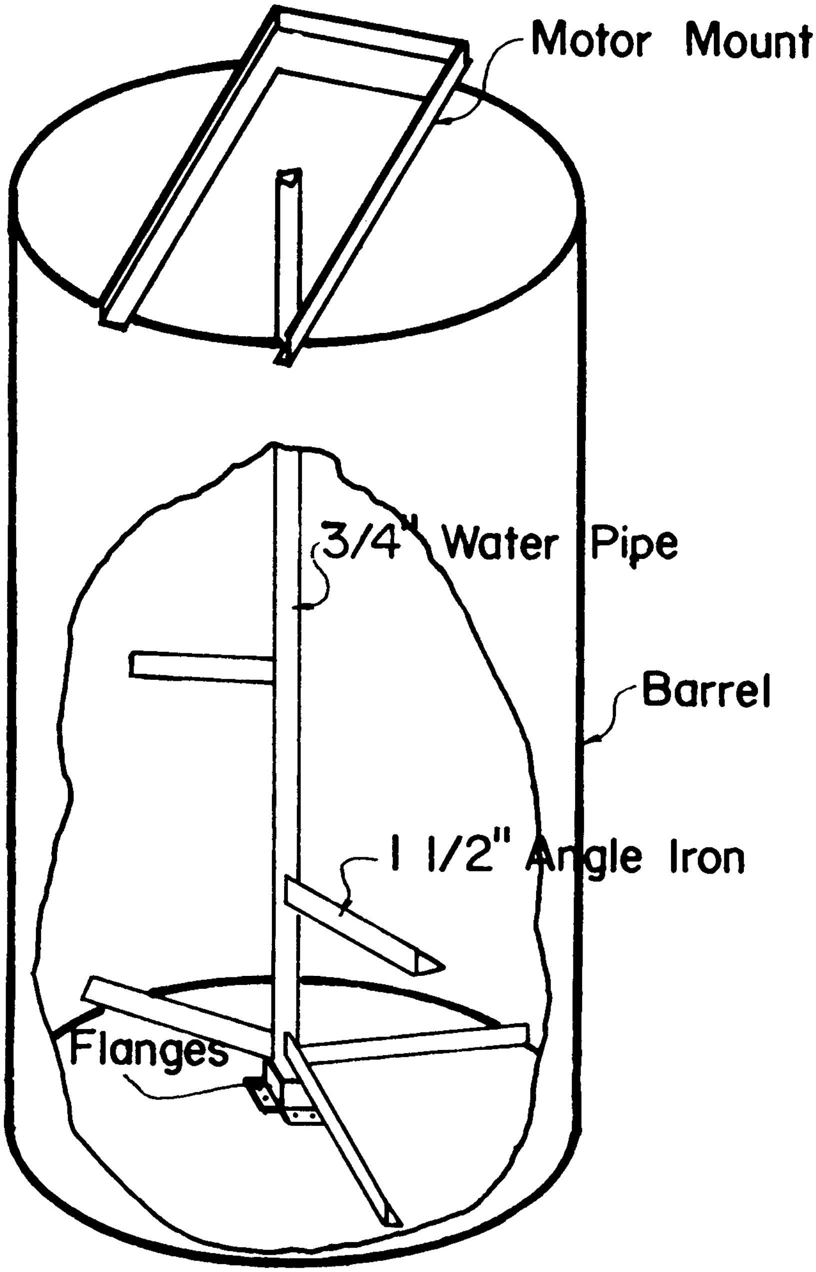

Figure 30. Cutaway section of mixing chamber

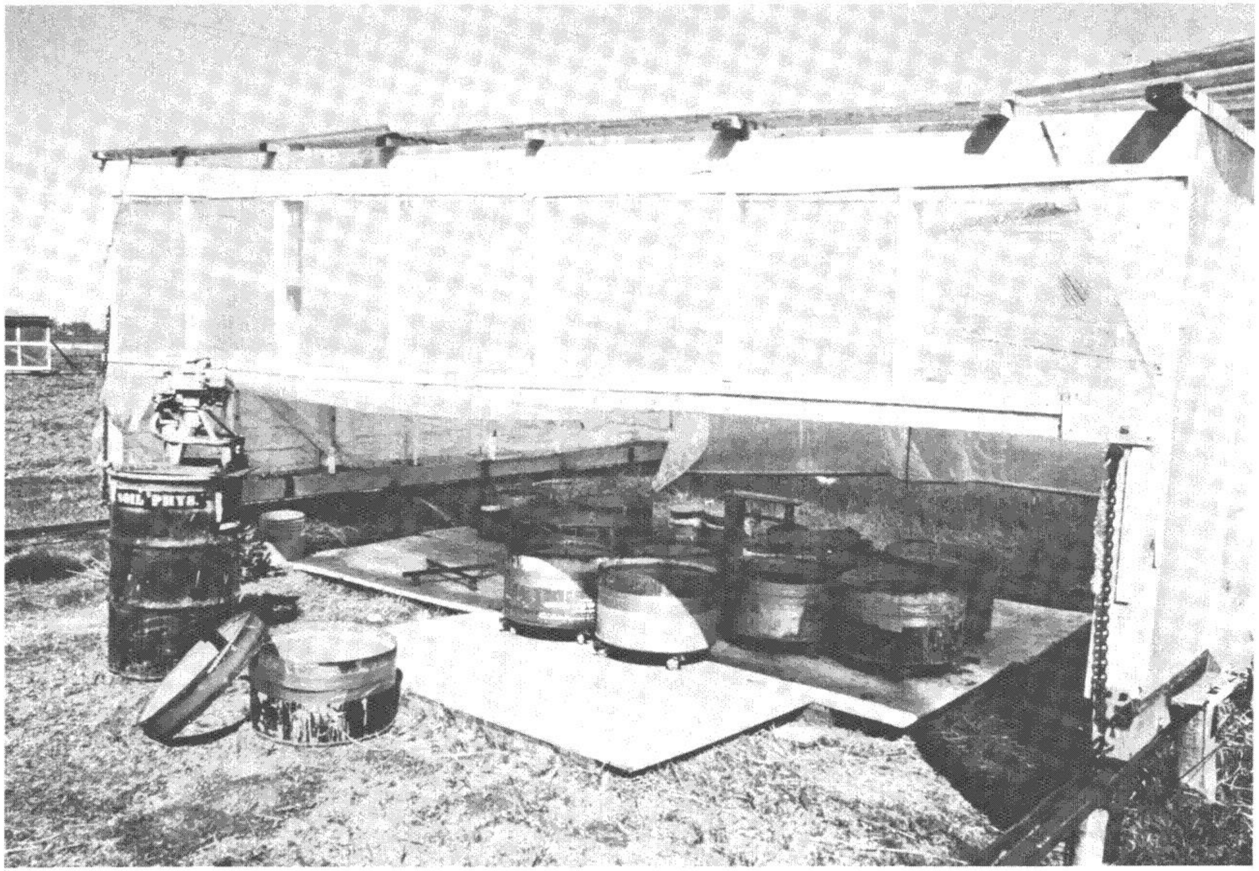

Figure 31. General view of the field location showing containers of dredged material and the rain shelter in place over the experimental area. The barrel in which the material was mixed and the soil auger head are shown on the left

Figure 32. General view of the field location showing the containers of dredged material, the scale, and the rain shelter in the off position

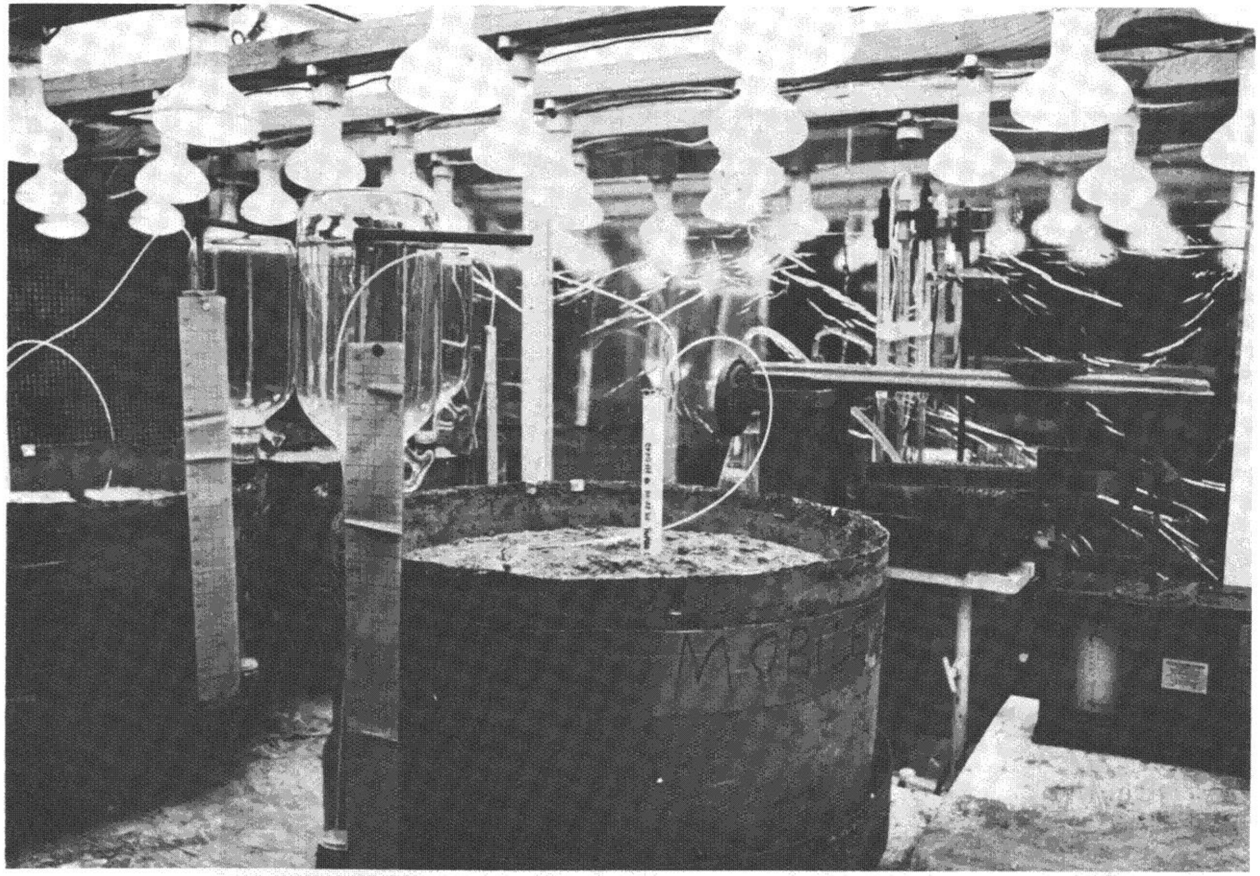

Figure 33. General view of environmental chamber showing the hygrothermograph on left. A container of dredged material from Mobile is on the platform scale in the center. The manometer attached to the barrel was used to determine the suction on the tensiometer

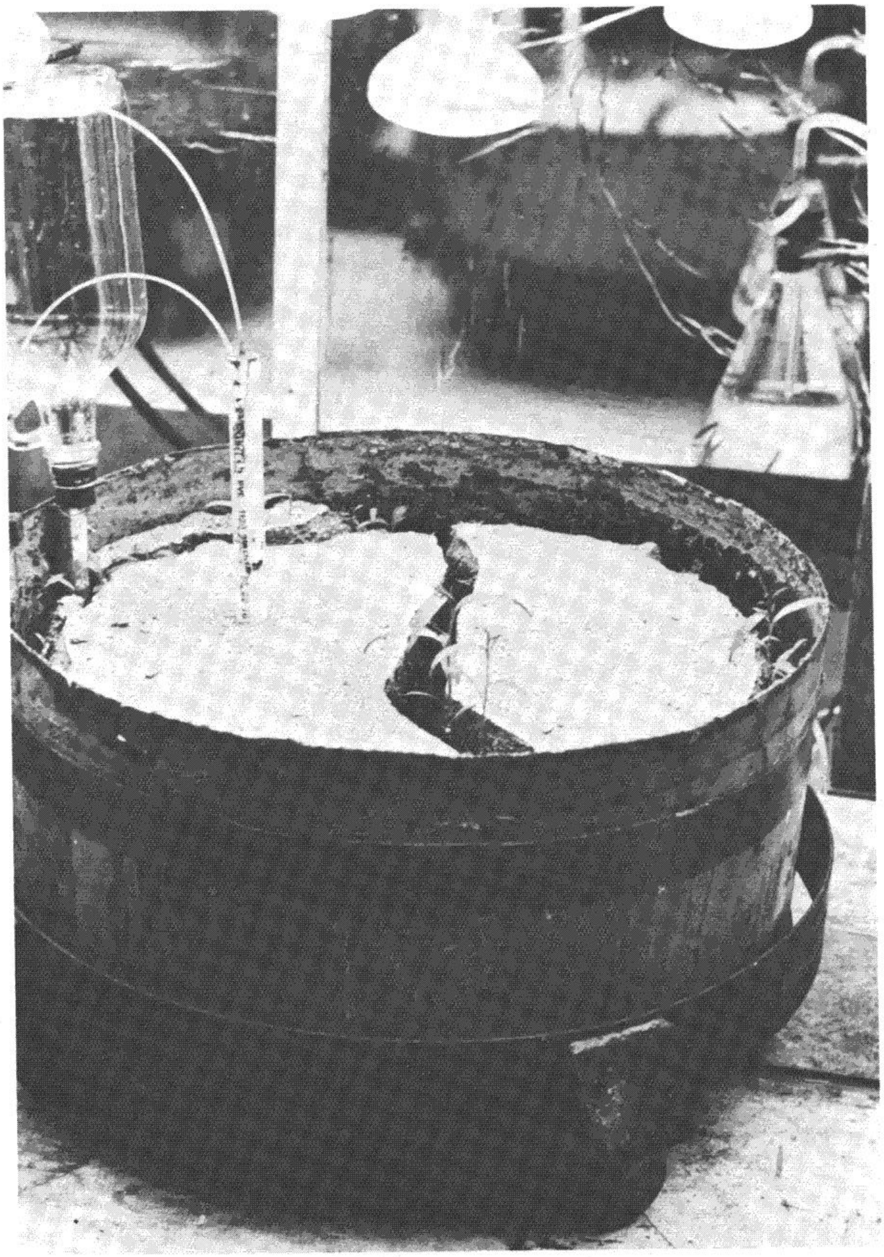

Figure 34. Container of dredged material from Toledo in the environmental chamber during an experiment with a constant water table. The inverted bottle provided water on demand to the bottom of the containers. The protruding tube in the center was connected to a tensiometer

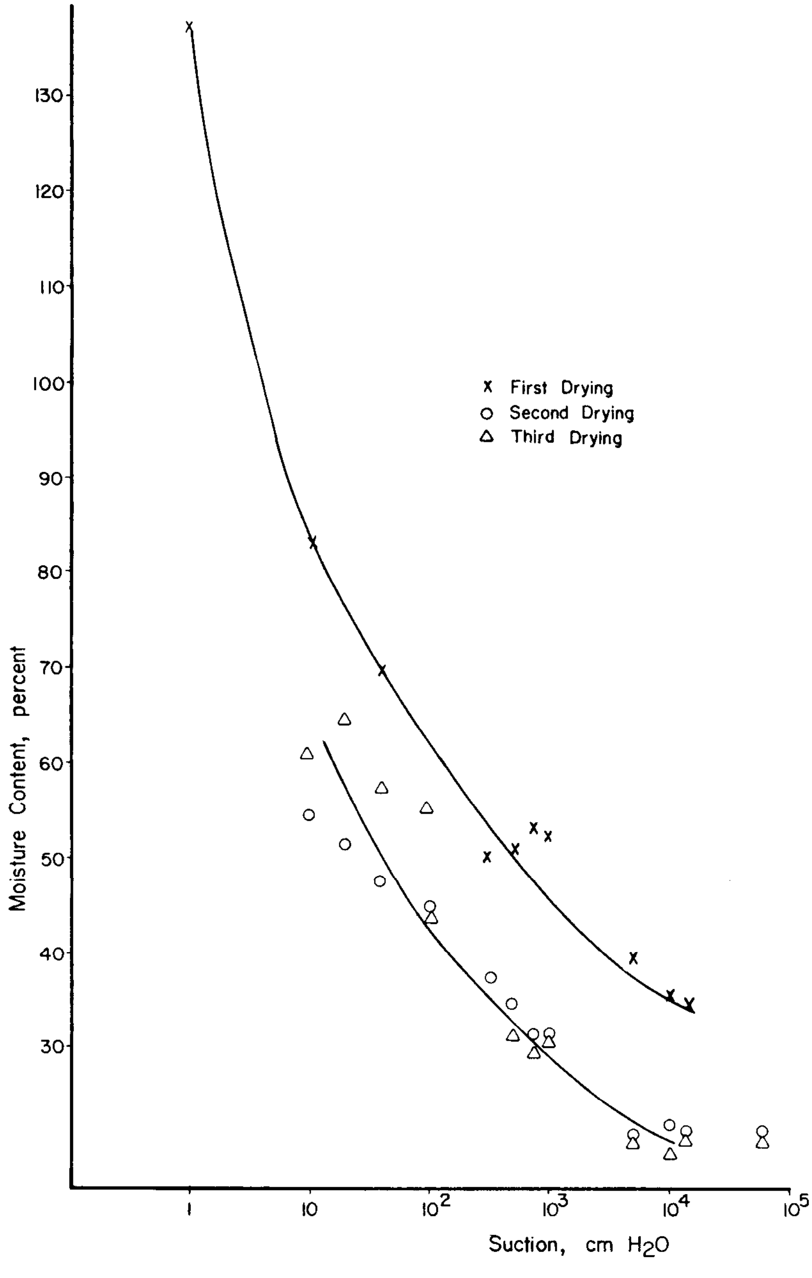

Figure 35. The percent moisture content by weight retained by the Philadelphia dredged material as a function of the suction for two successive drying cycles

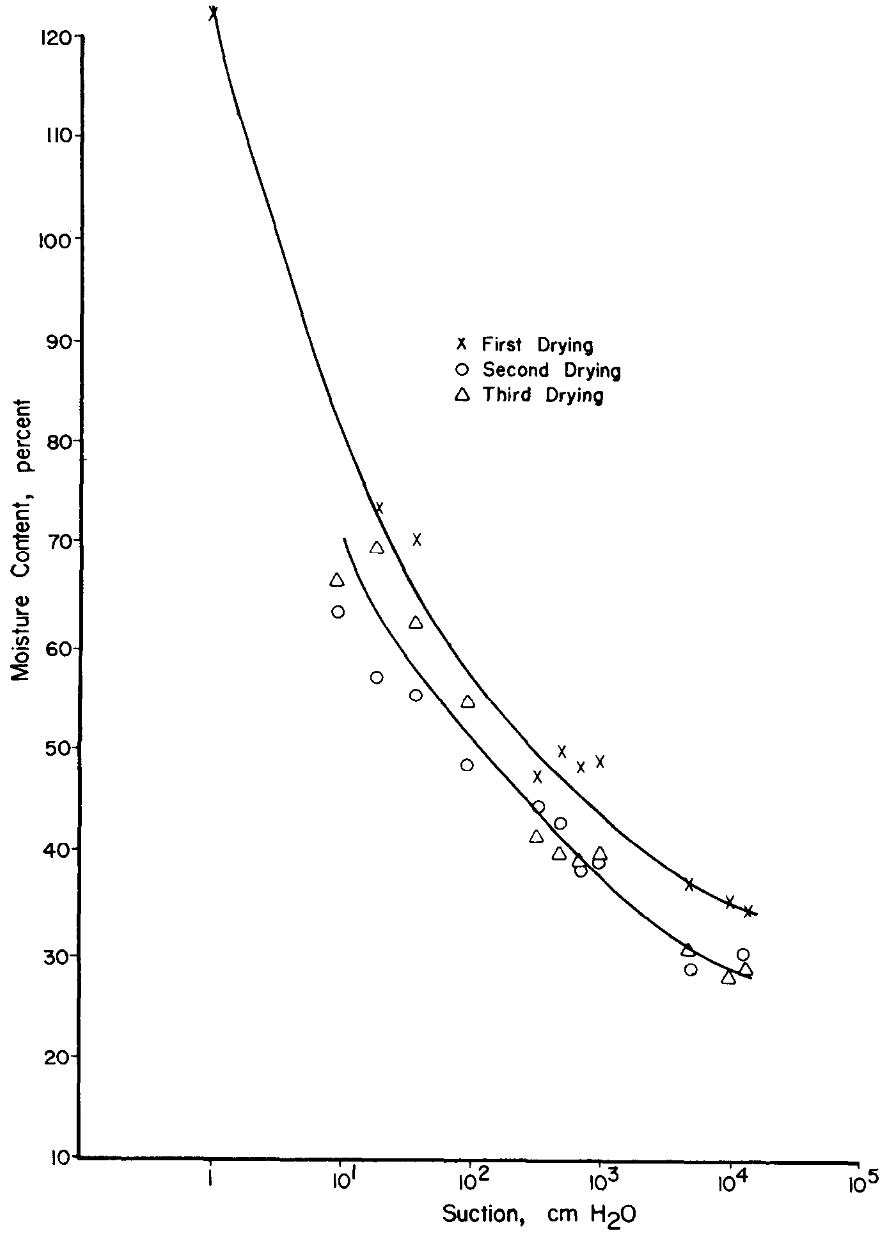

Figure 36. The percent moisture content by weight retained by the Toledo dredged material as a function of the suction for two successive drying cycles

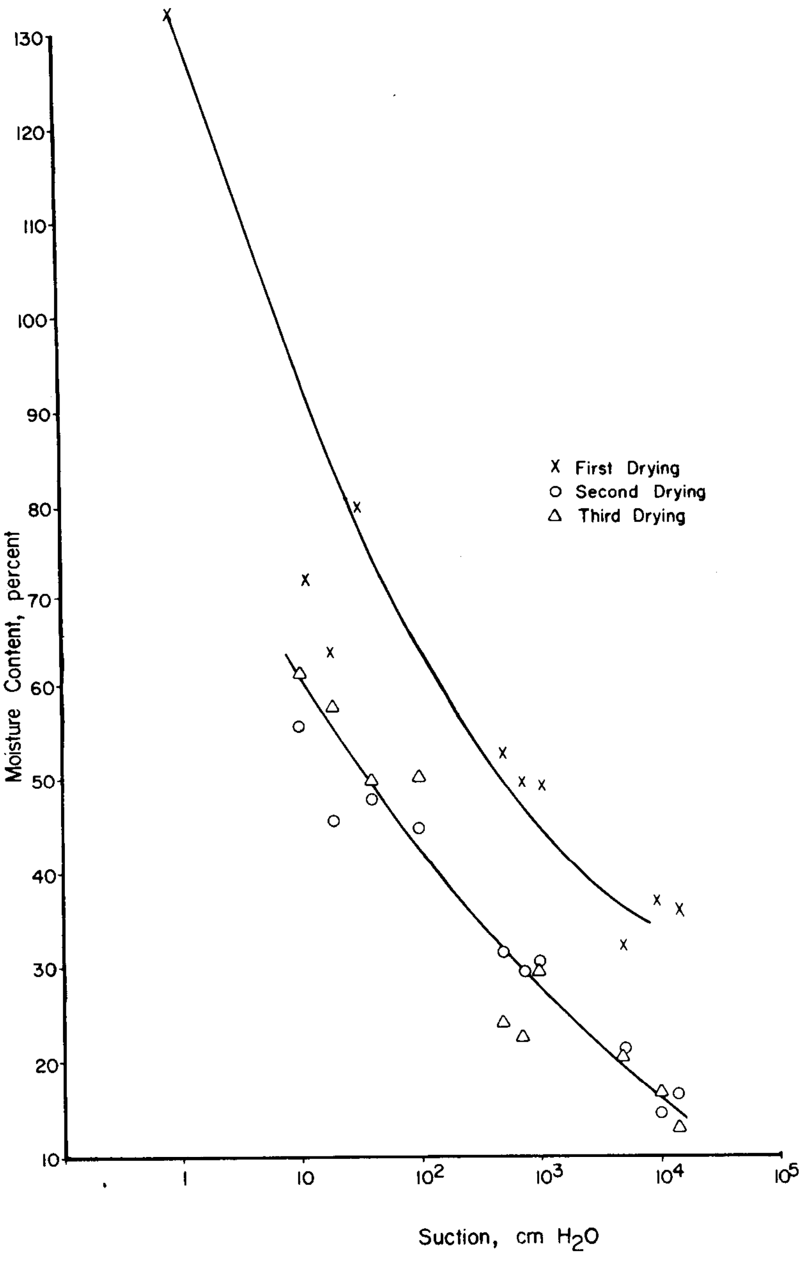

Figure 37. The percent moisture content by weight retained by the Norfolk dredged material as a function of the suction for two successive drying cycles

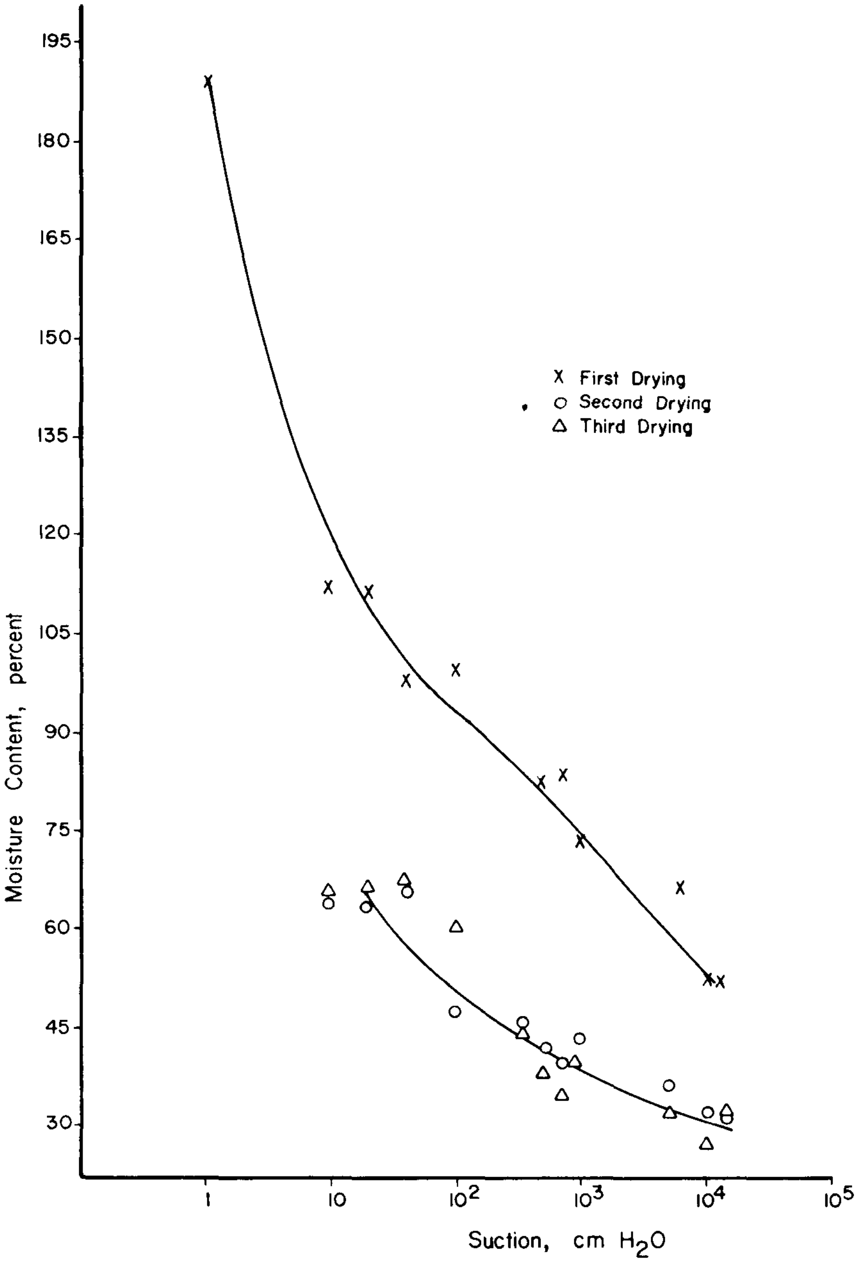

Figure 38. The percent moisture content by weight retained by the Mobile dredged material as a function of the suction for two successive drying cycles

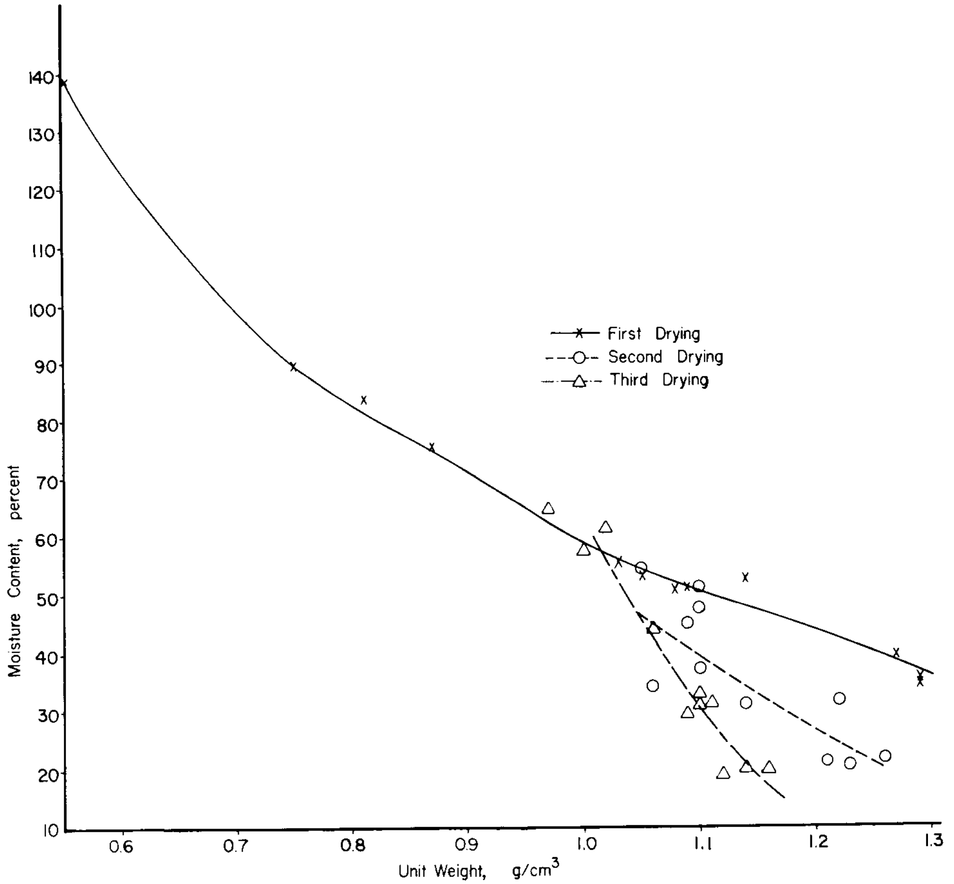

Figure 39. Unit weight of the Philadelphia dredged material through three drying cycles as a function of the percent moisture

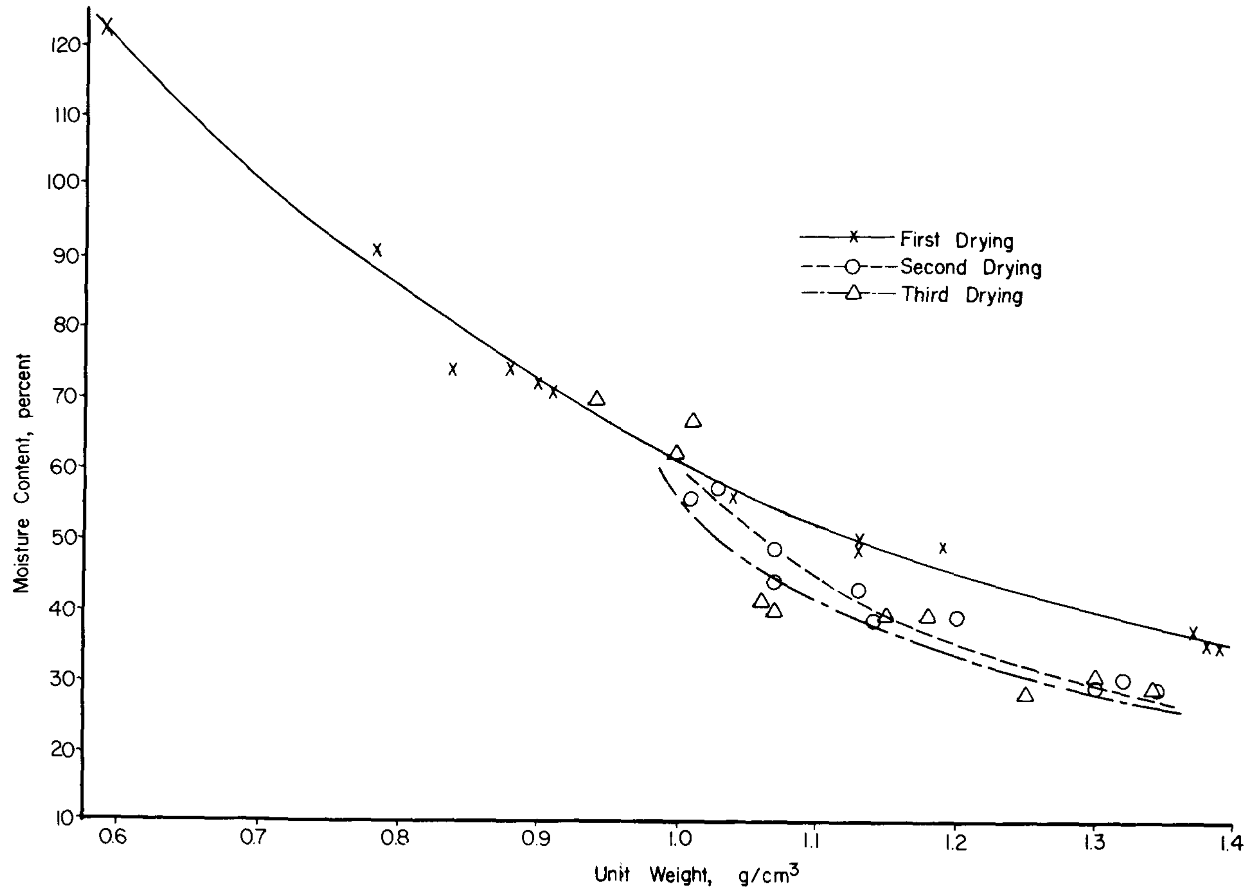

Figure 40. Unit weight of the Toledo dredged material through three drying cycles as a function of the percent moisture

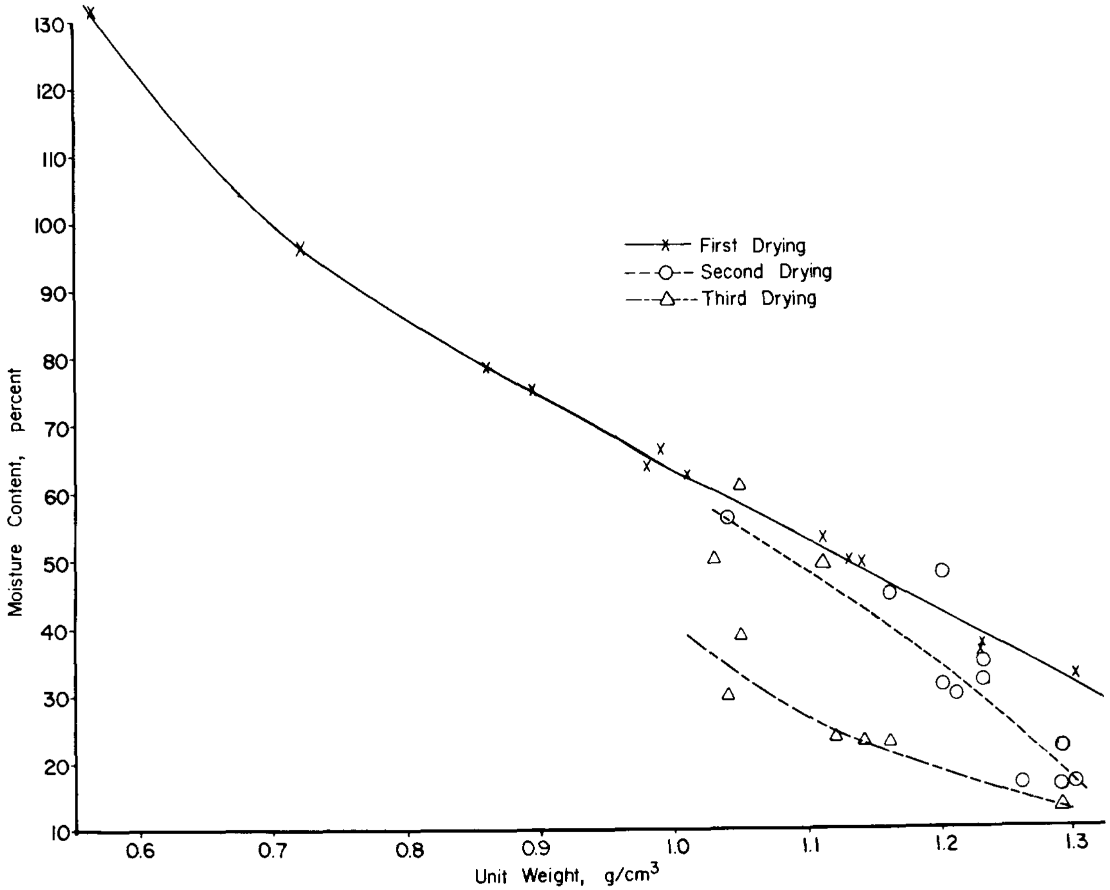

Figure 41. Unit weight of the Norfolk dredged material through three drying cycles as a function of the percent moisture

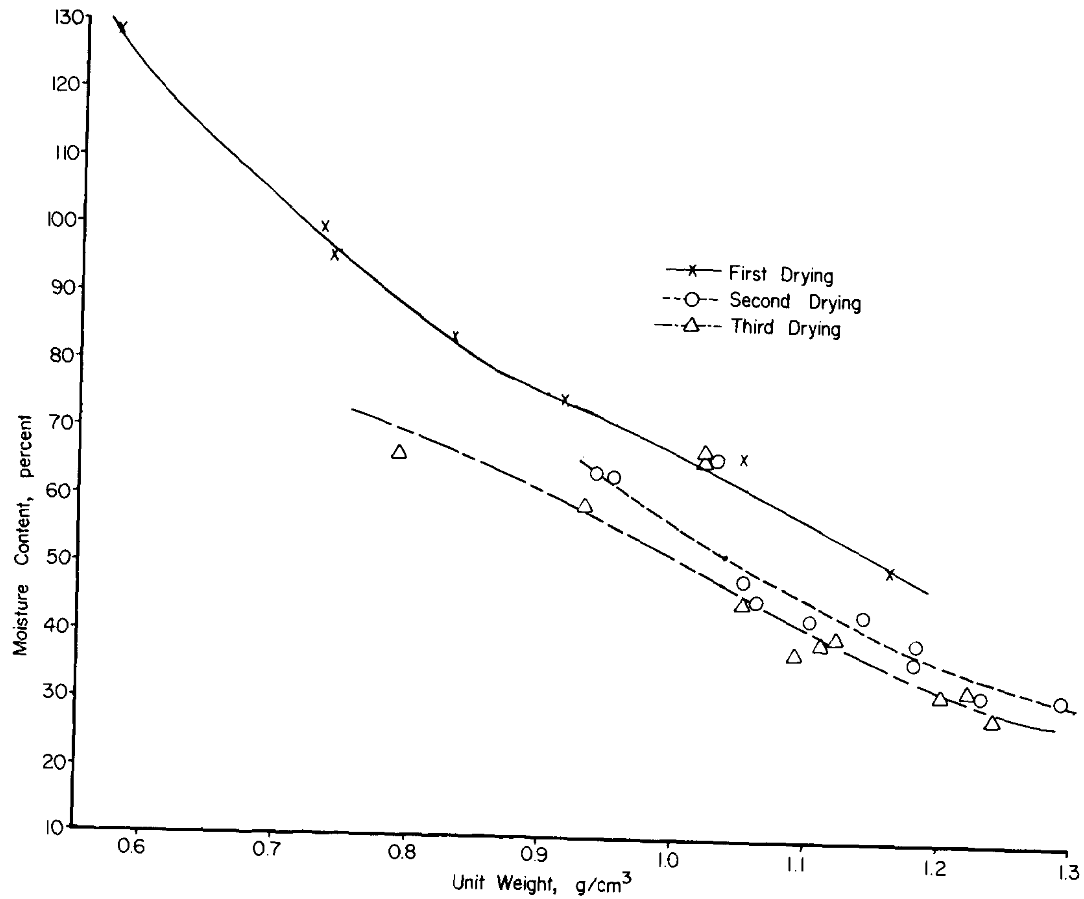

Figure 42. Unit weight of the Mobile dredged material through three drying cycles as a function of the percent moisture

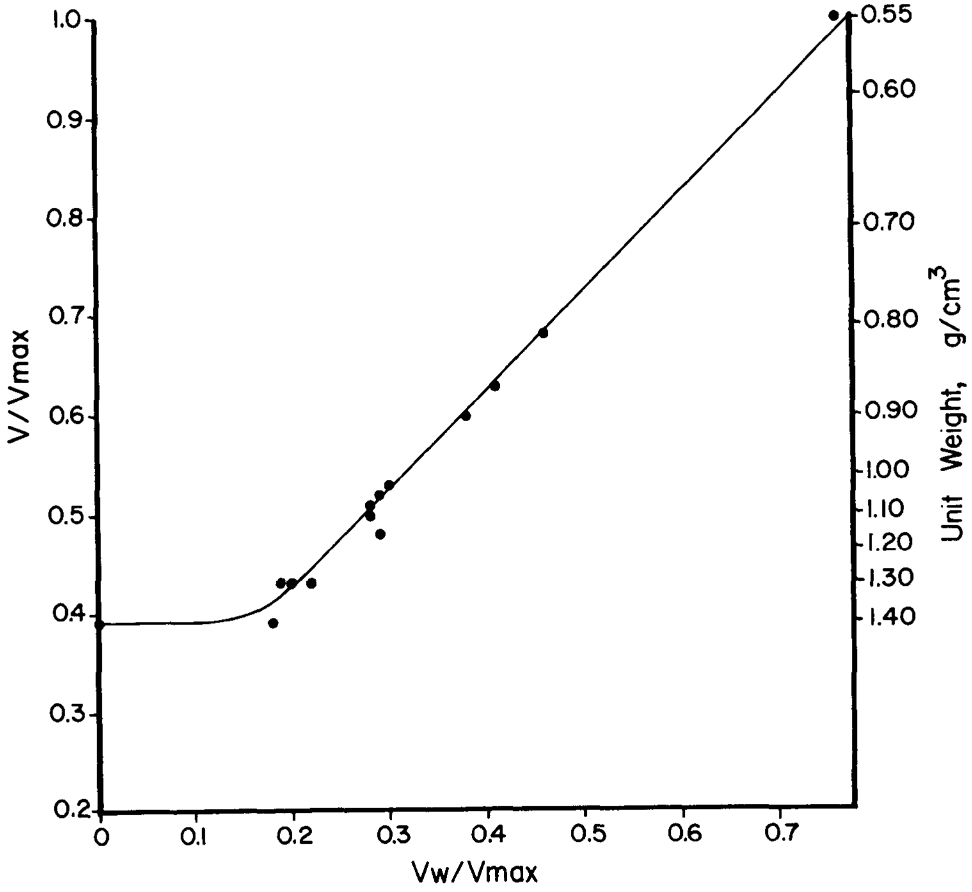

Figure 43. The volume reduction as a function of the volume of water lost for the Philadelphia dredged material

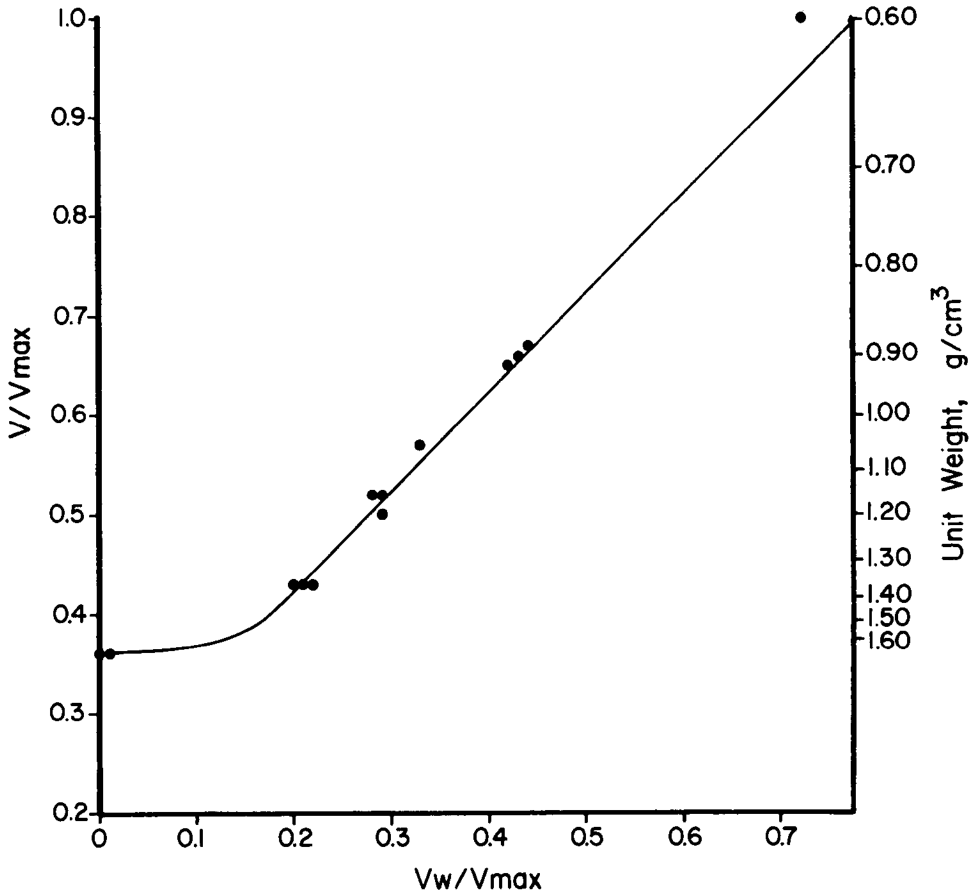

Figure 44. The volume reduction as a function of the volume of water lost for the Toledo dredged material

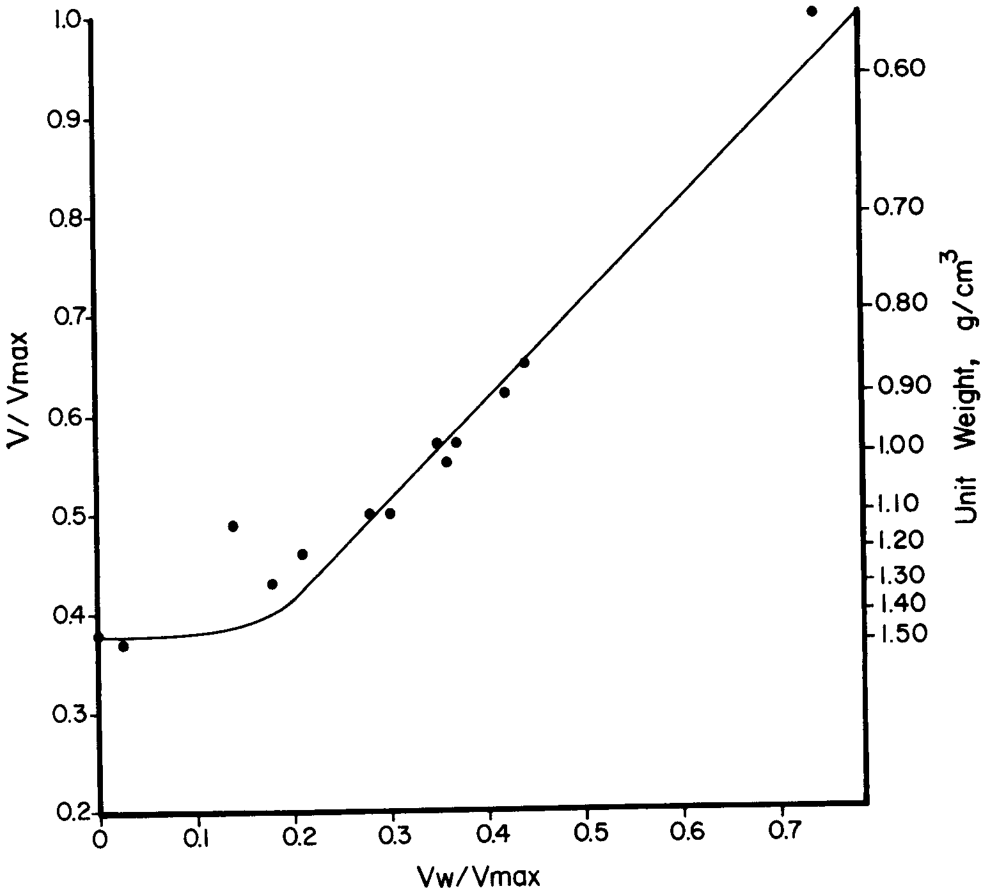

Figure 45. The volume reduction as a function of the volume of water lost for the Norfolk dredged material

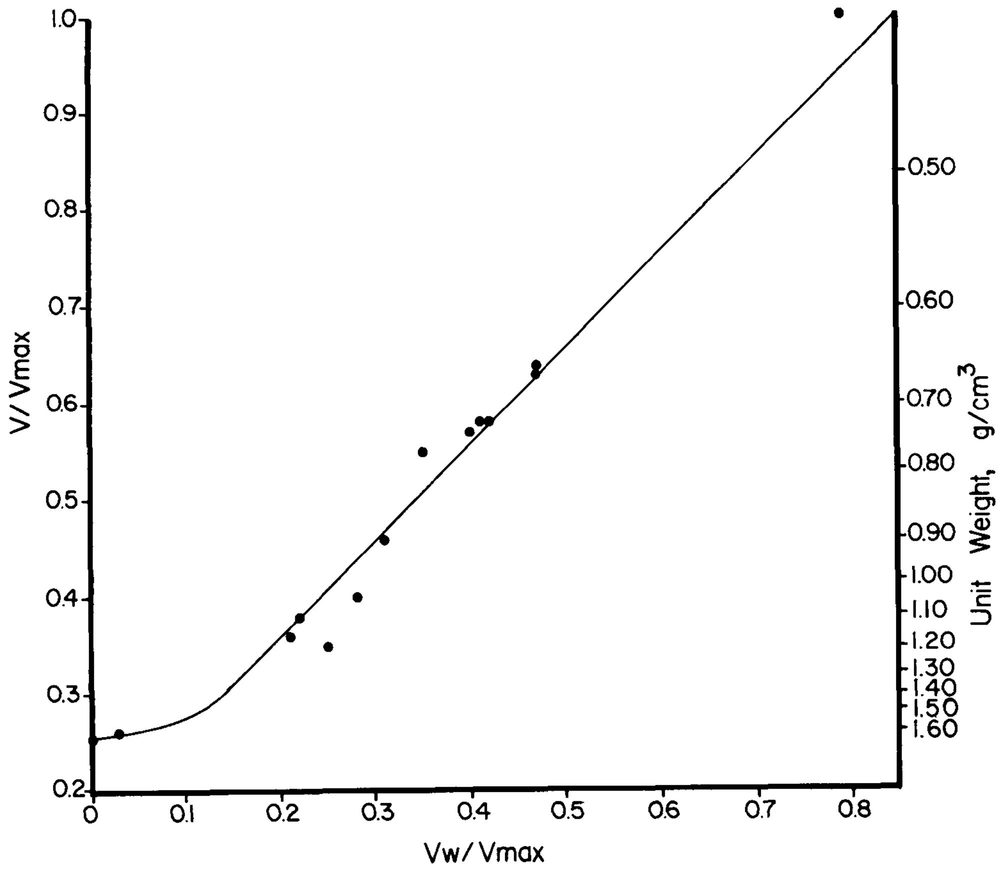

Figure 46. The volume reduction as a function of the volume of water lost for the Mobile dredged material

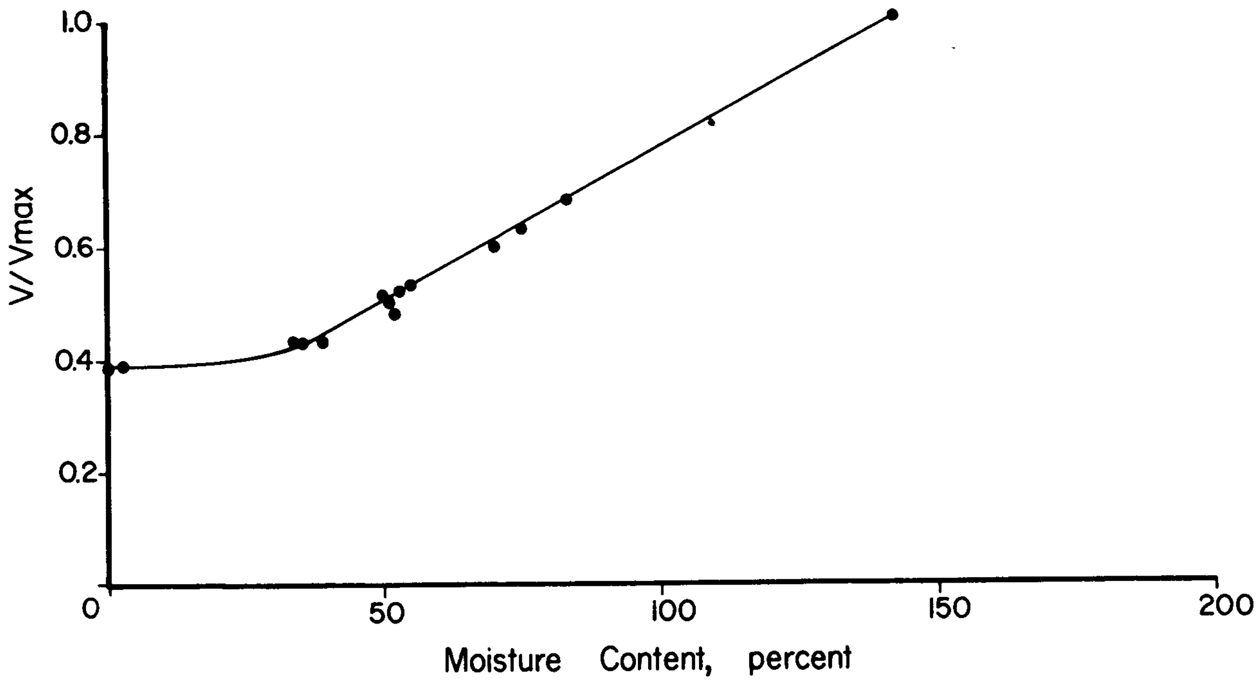

Figure 47. The volume reduction as a function of the moisture content for the Philadelphia dredged material

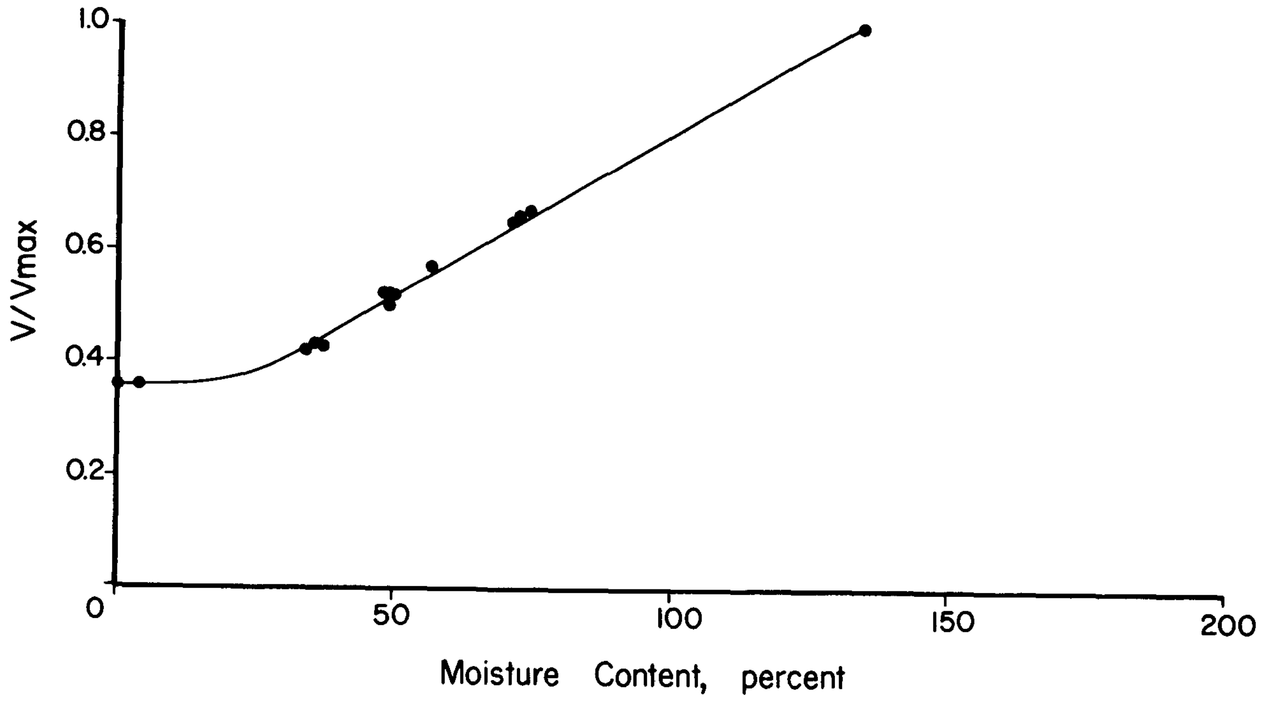

Figure 48. The volume reduction as a function of the moisture content for the Toledo dredged material

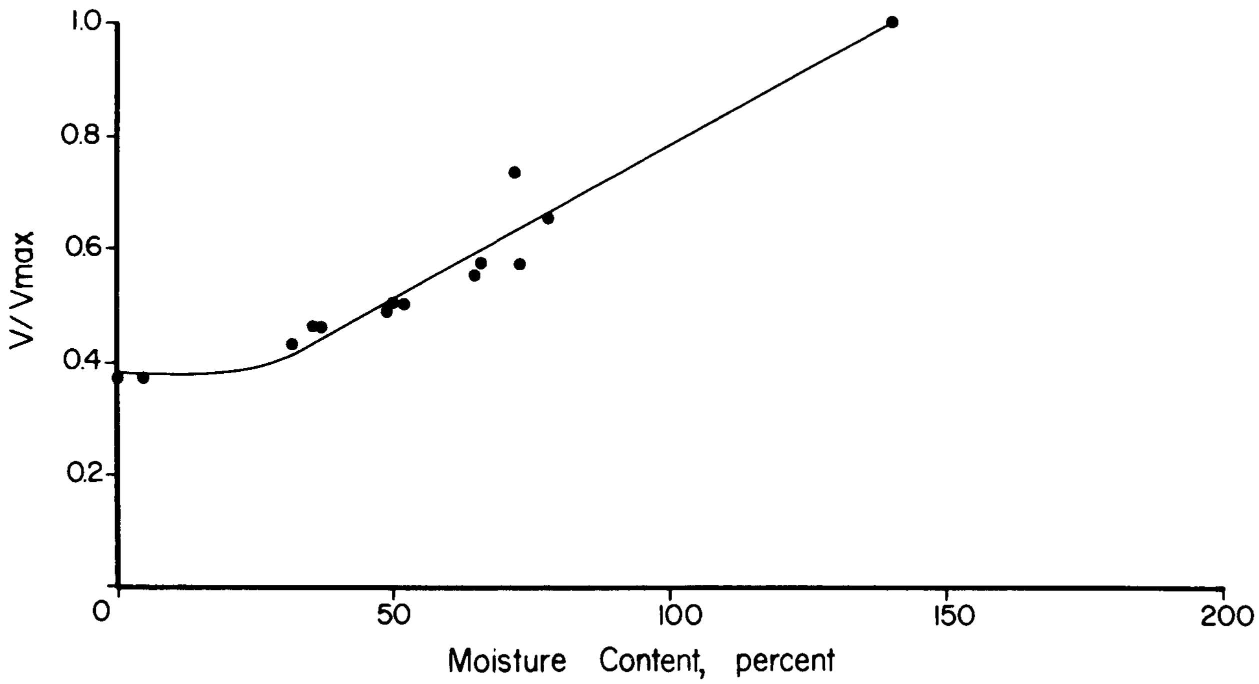

Figure 49. The volume reduction as a function of the moisture content for the Norfolk dredged material

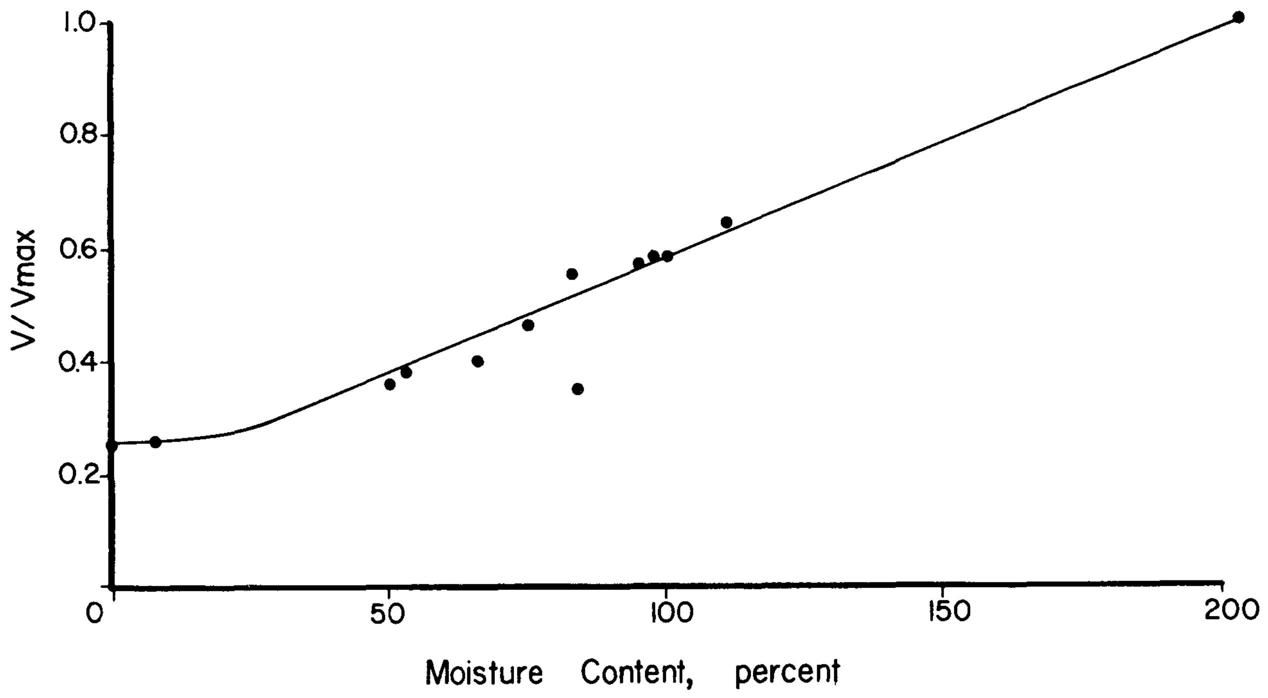

Figure 50. The volume reduction as a function of the moisture content for the Mobile dredged material

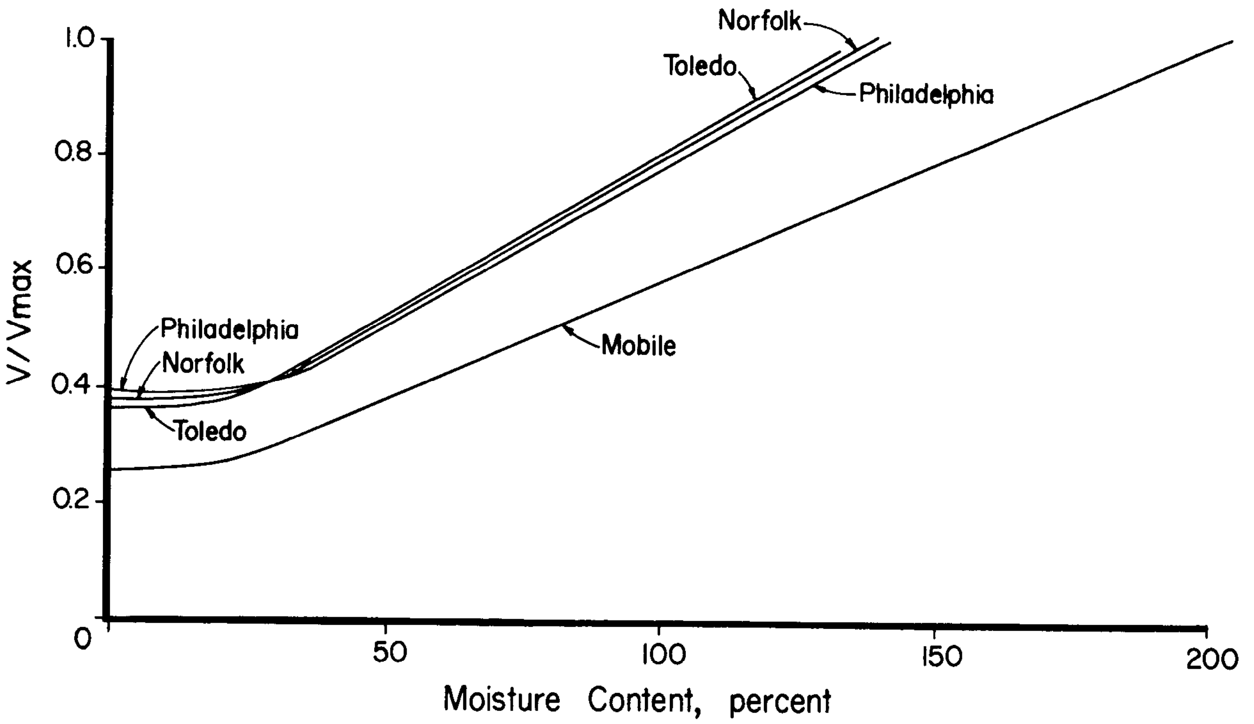

Figure 51. The volume reduction as a function of the soil moisture content for all four dredged materials

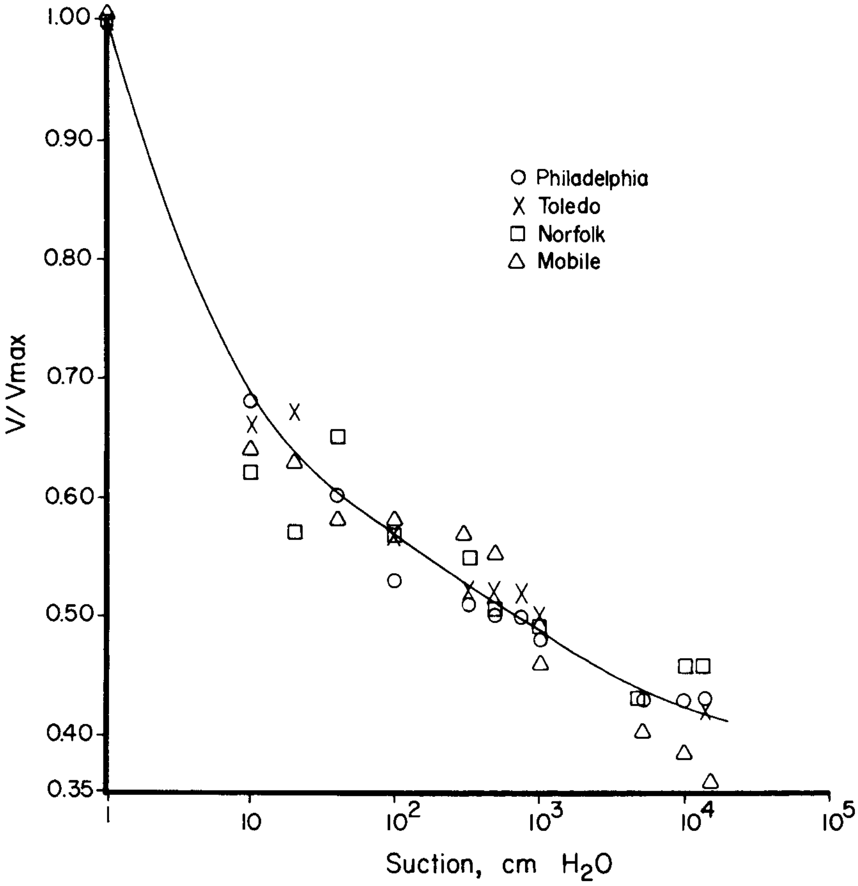

Figure 52. The volume reduction as a function of the suction for all four dredged materials

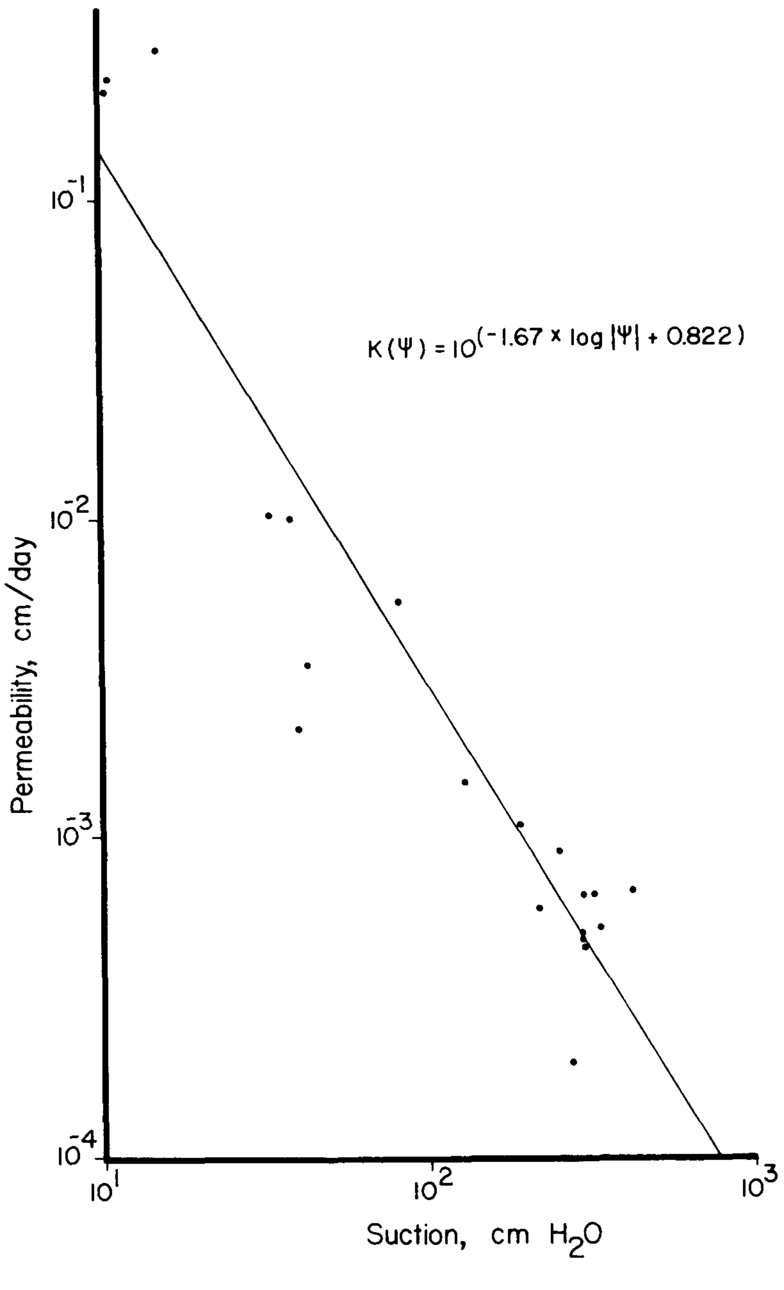

Figure 53. Permeability as a function of the suction for the Philadelphia dredged material

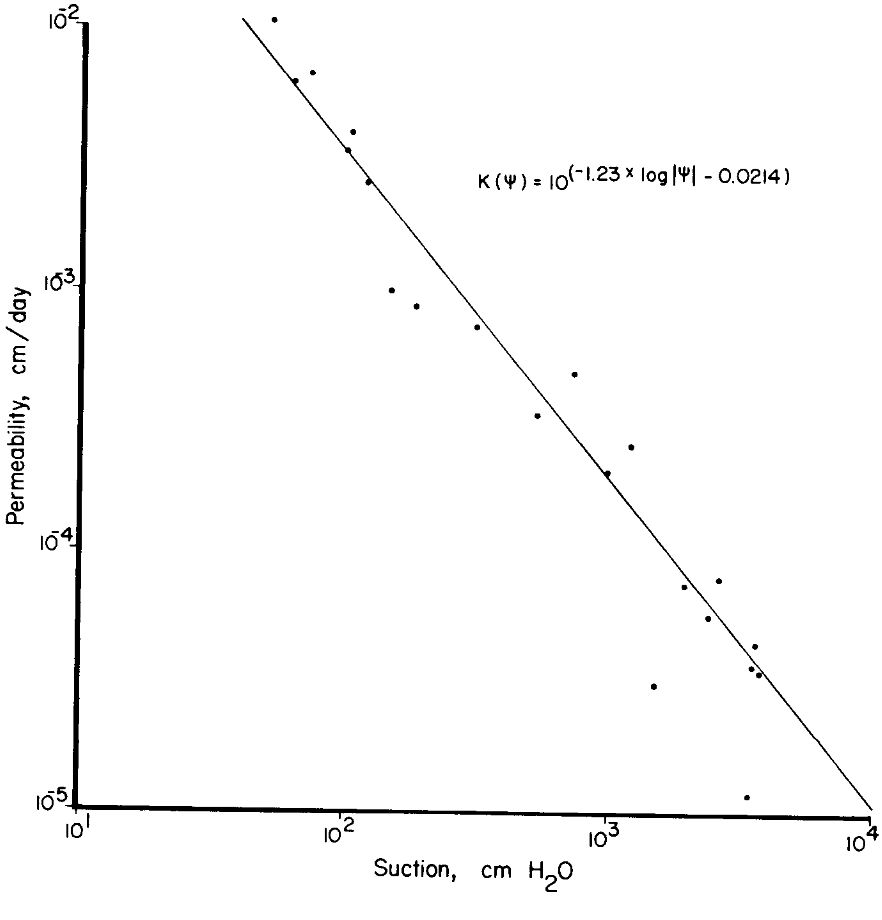

Figure 54. Permeability as a function of the suction for the Toledo dredged material

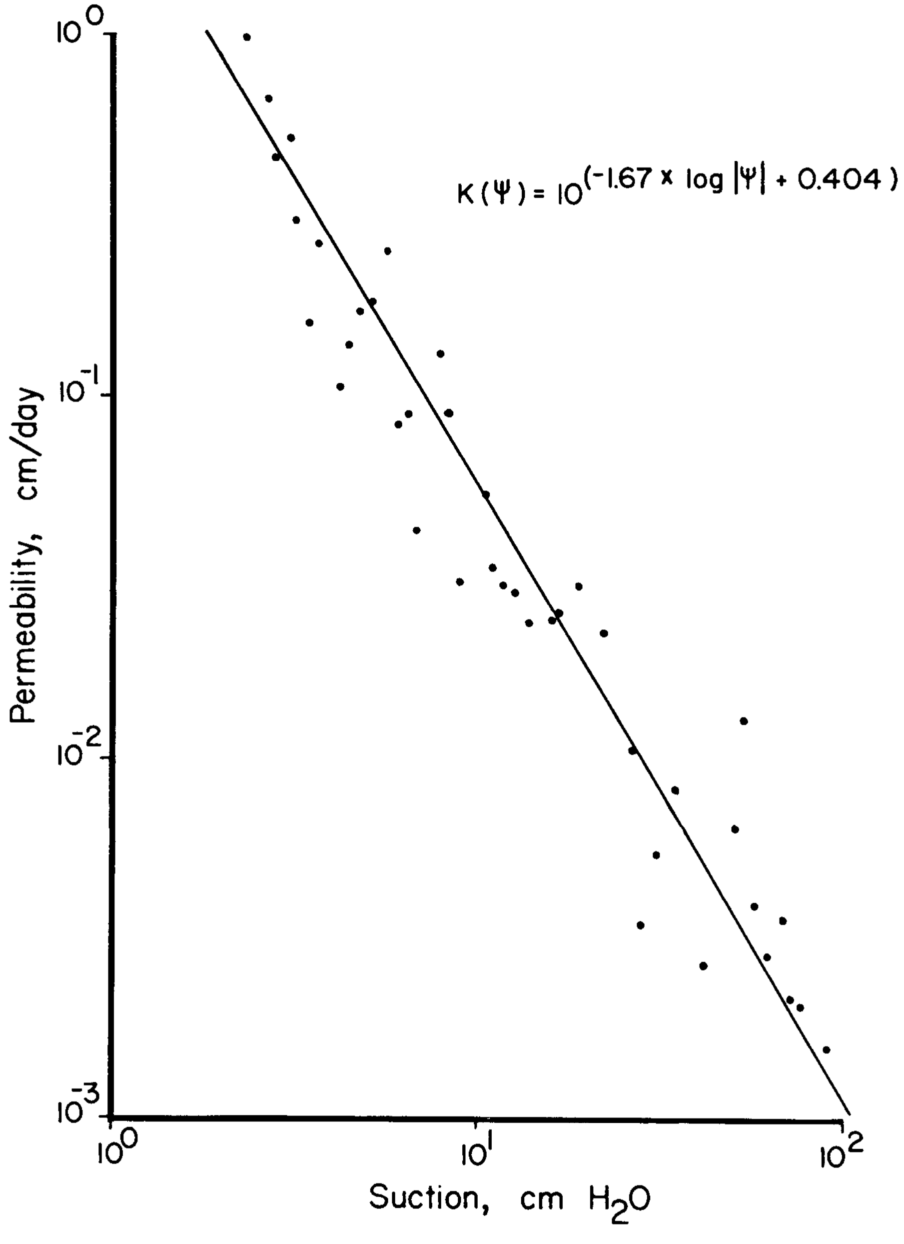

Figure 55. Permeability as a function of the suction for the Mobile dredged material

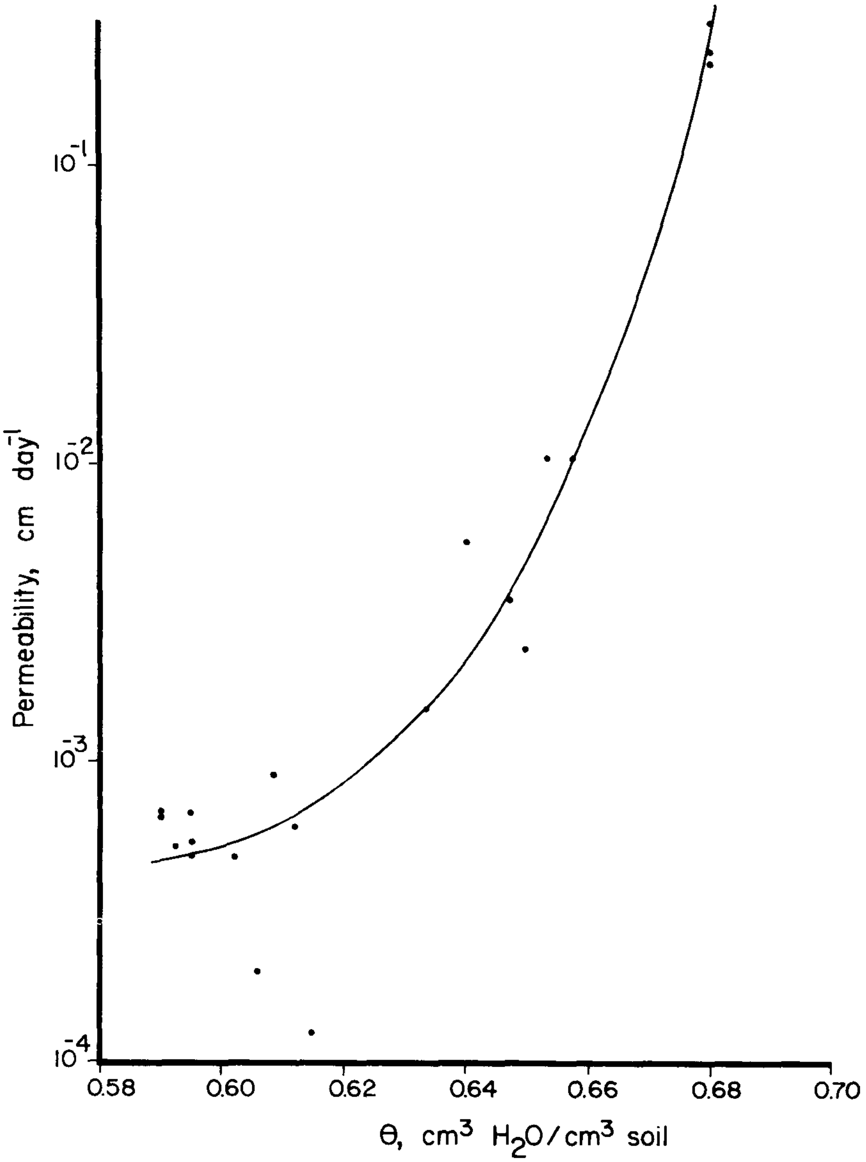

Figure 56. Permeability as a function of the moisture content for the Philadelphia dredged material

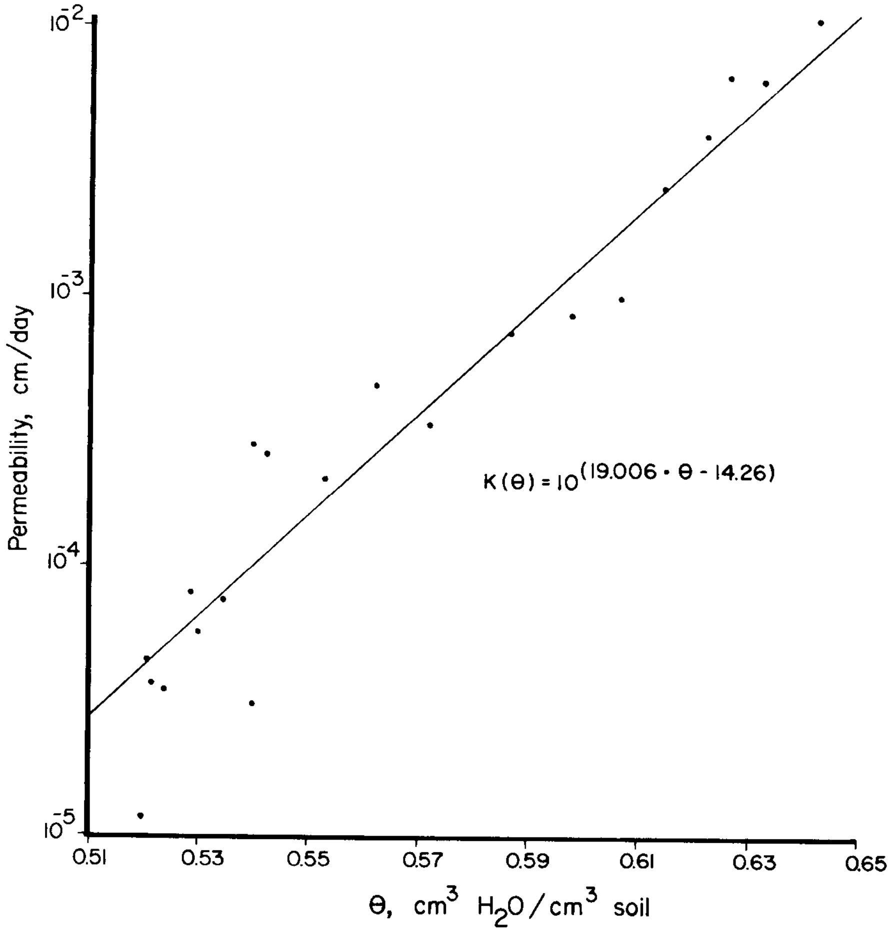

Figure 57. Permeability as a function of the moisture content for the Toledo dredged material

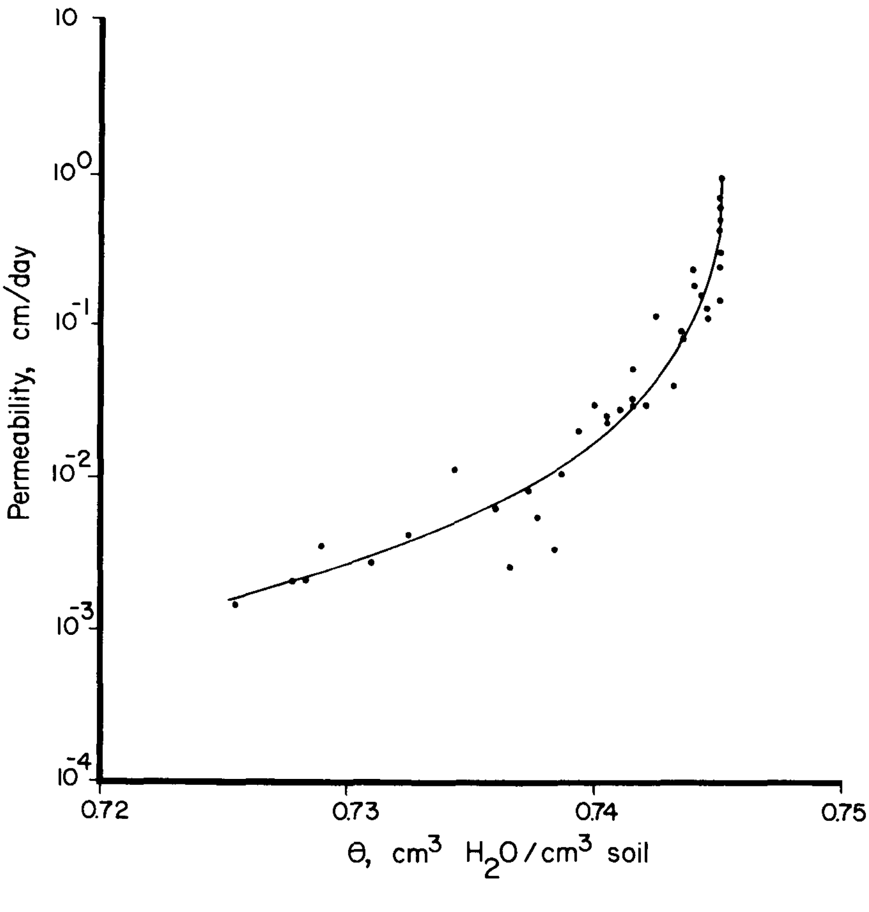

Figure 58. Permeability as a function of the moisture content for the Mobile dredged material

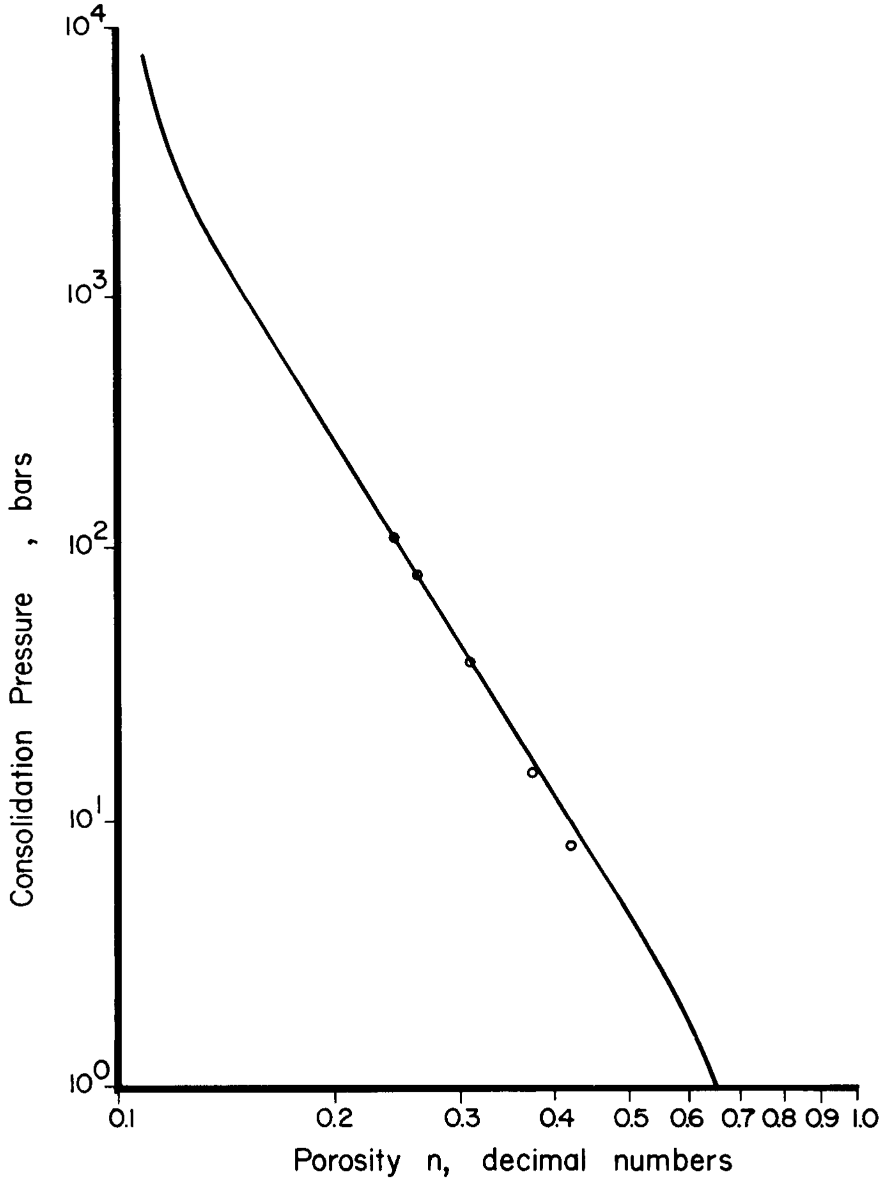

Figure 59. Porosity as a function of the consolidation pressure for the Norfolk dredged material

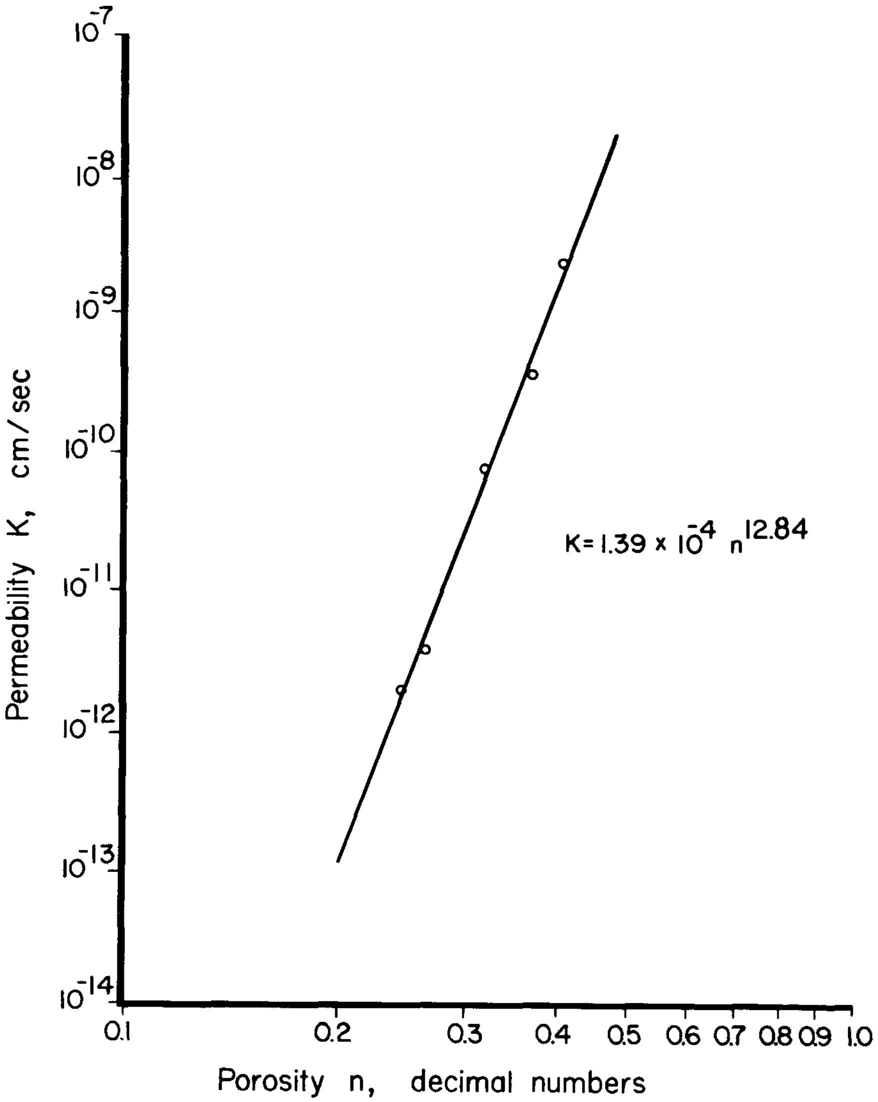

Figure 60. Permeability of the Norfolk material as a function of the porosity

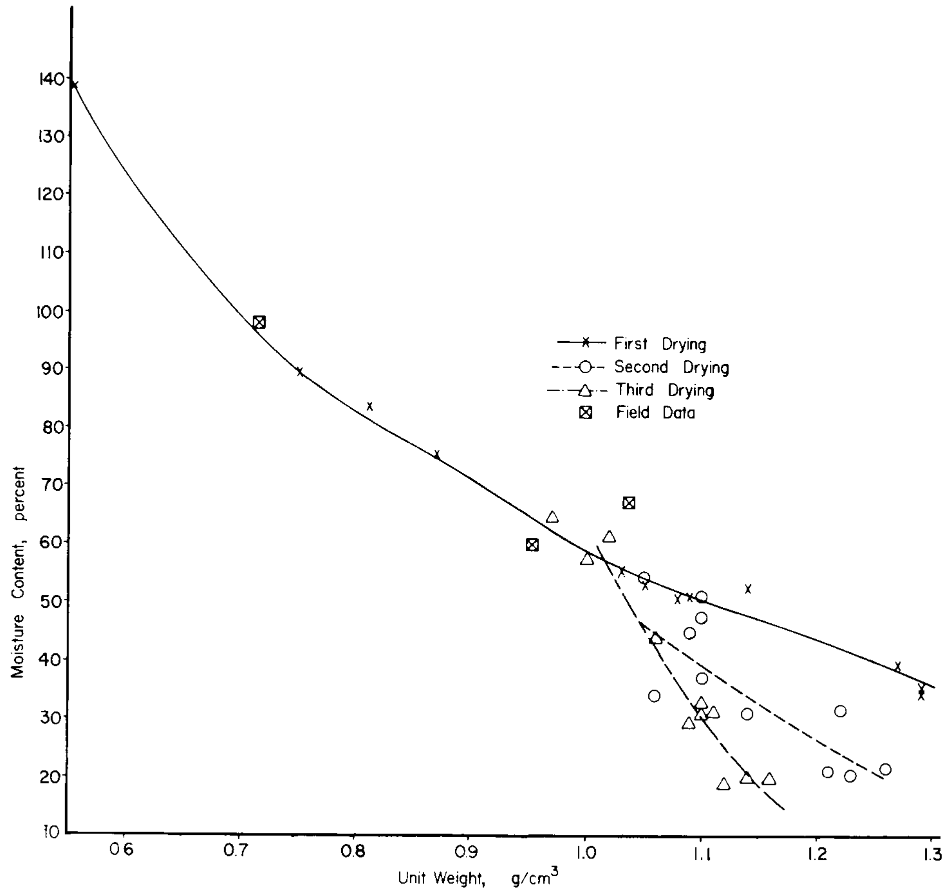

Figure 61. Bulk density of the Philadelphia dredged material through three drying cycles as a function of the moisture content

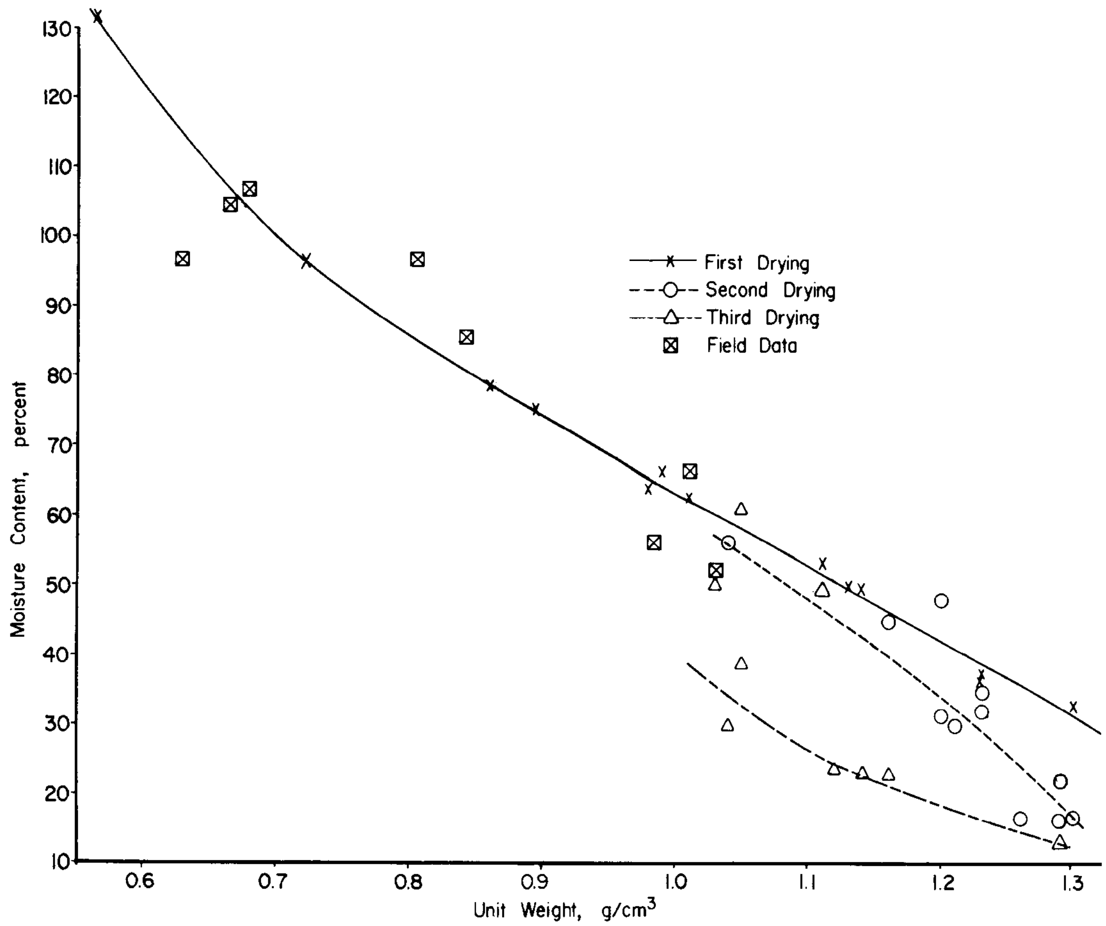

Figure 62. Bulk density of the Norfolk dredged material through three drying cycles as a function of the moisture content

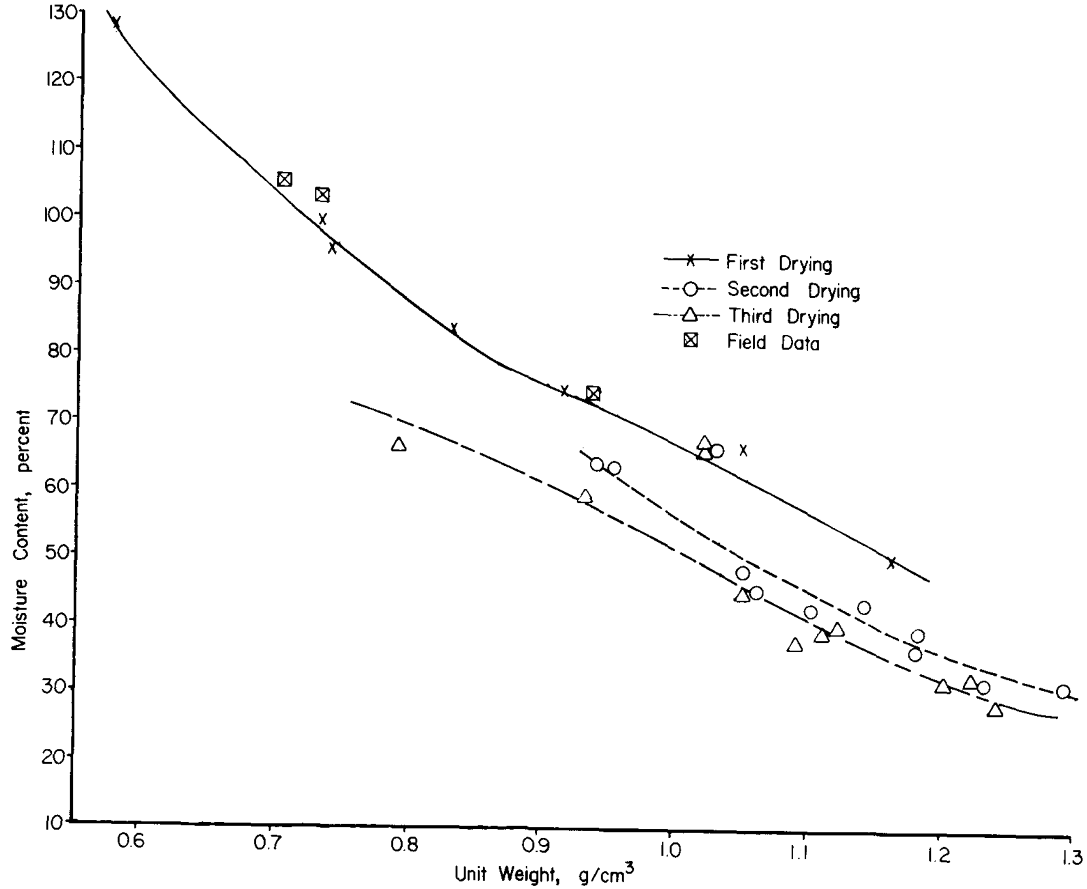

Figure 63. Bulk density of the Mobile dredged material through three drying cycles as a function of the moisture content

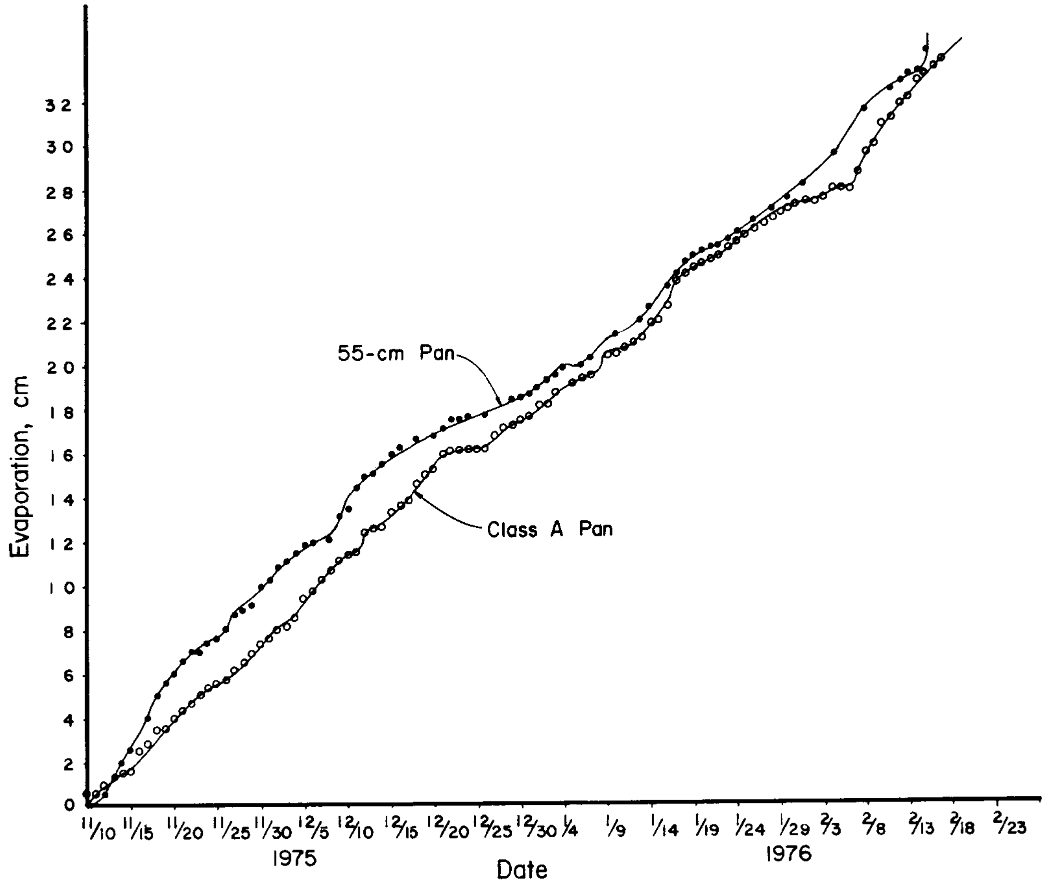

Figure 64. Cumulative evaporation from Class A pan and the 55-cm pan of water during Experiment B

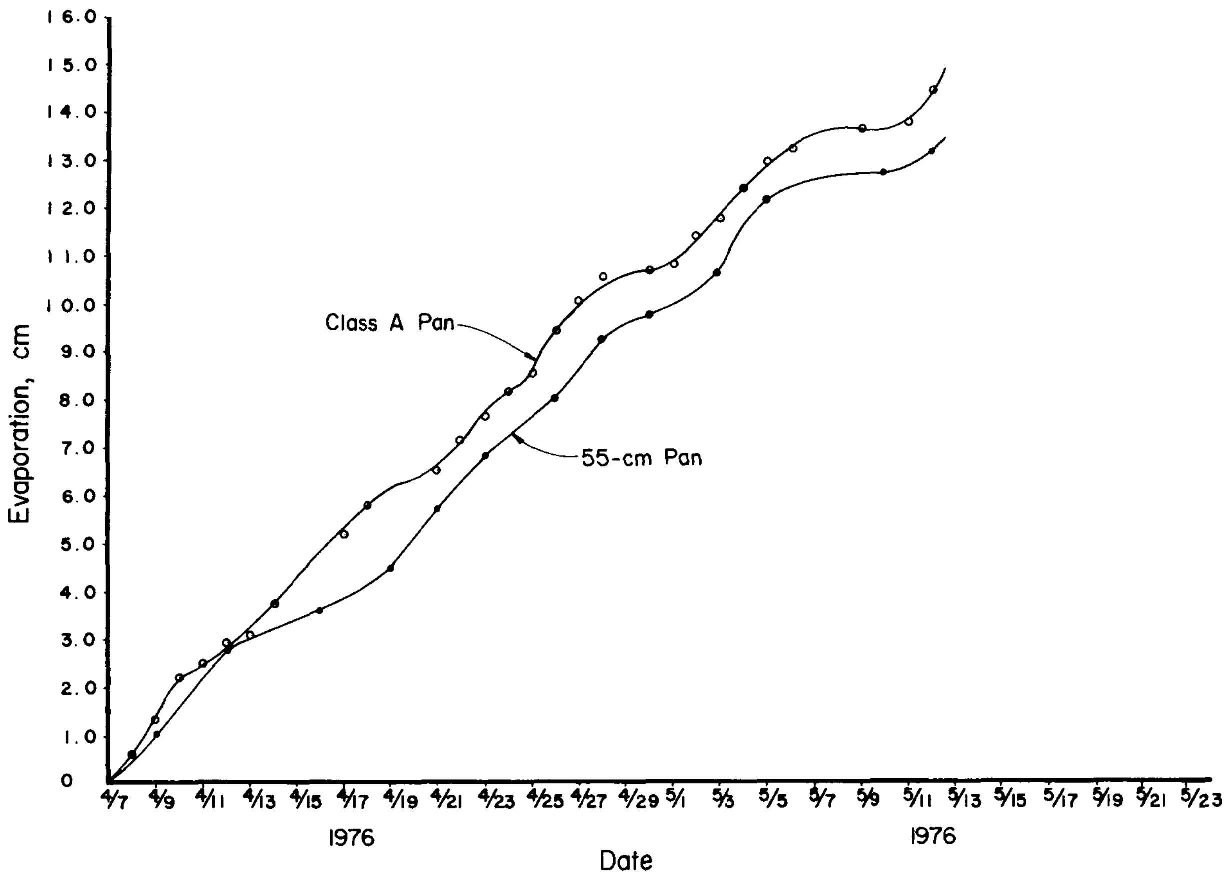

Figure 65. Cumulative evaporation from Class A pan and the 55-cm pan of water during Experiment D

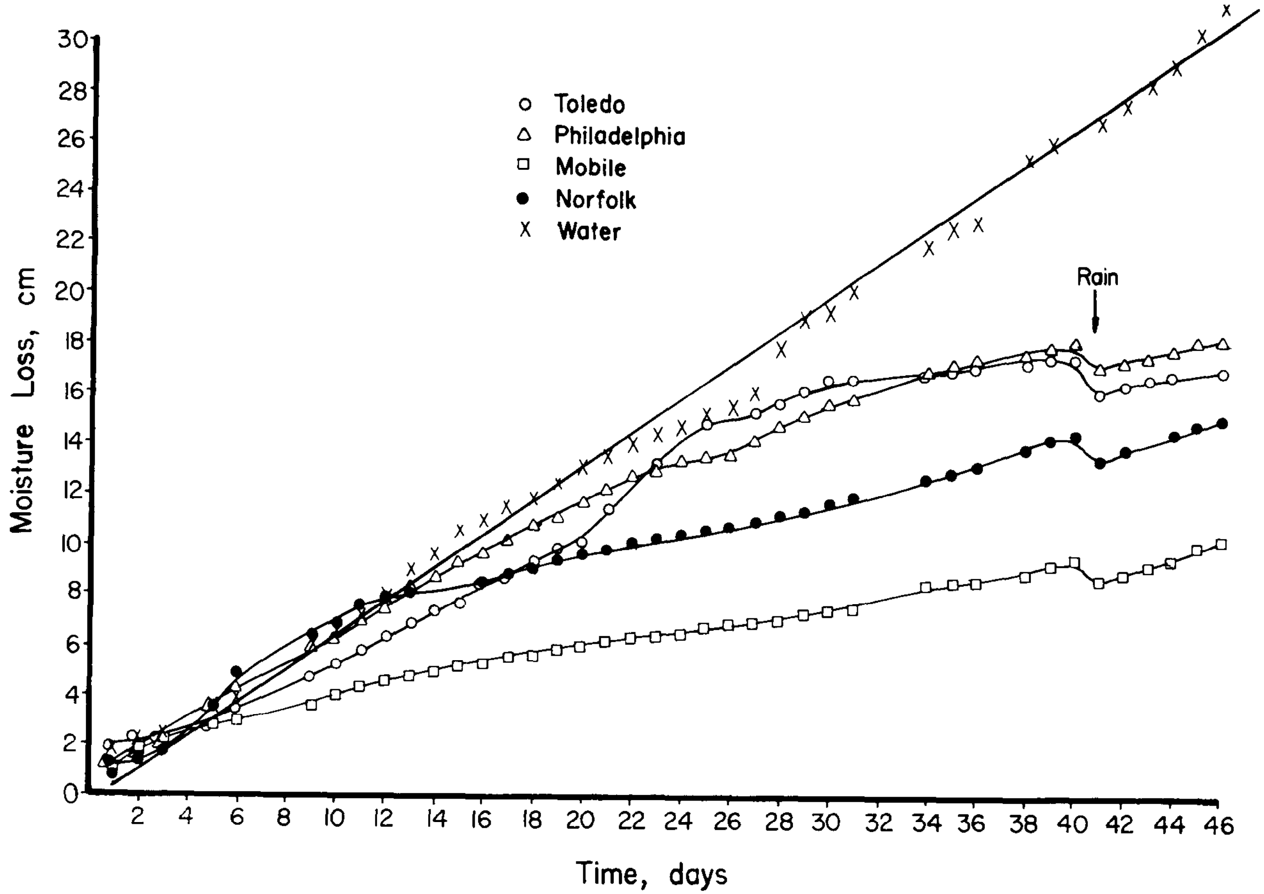

Figure 66. Cumulative moisture loss from each of the four dredged material samples and the free-water surface during Experiment A in the environmental chamber

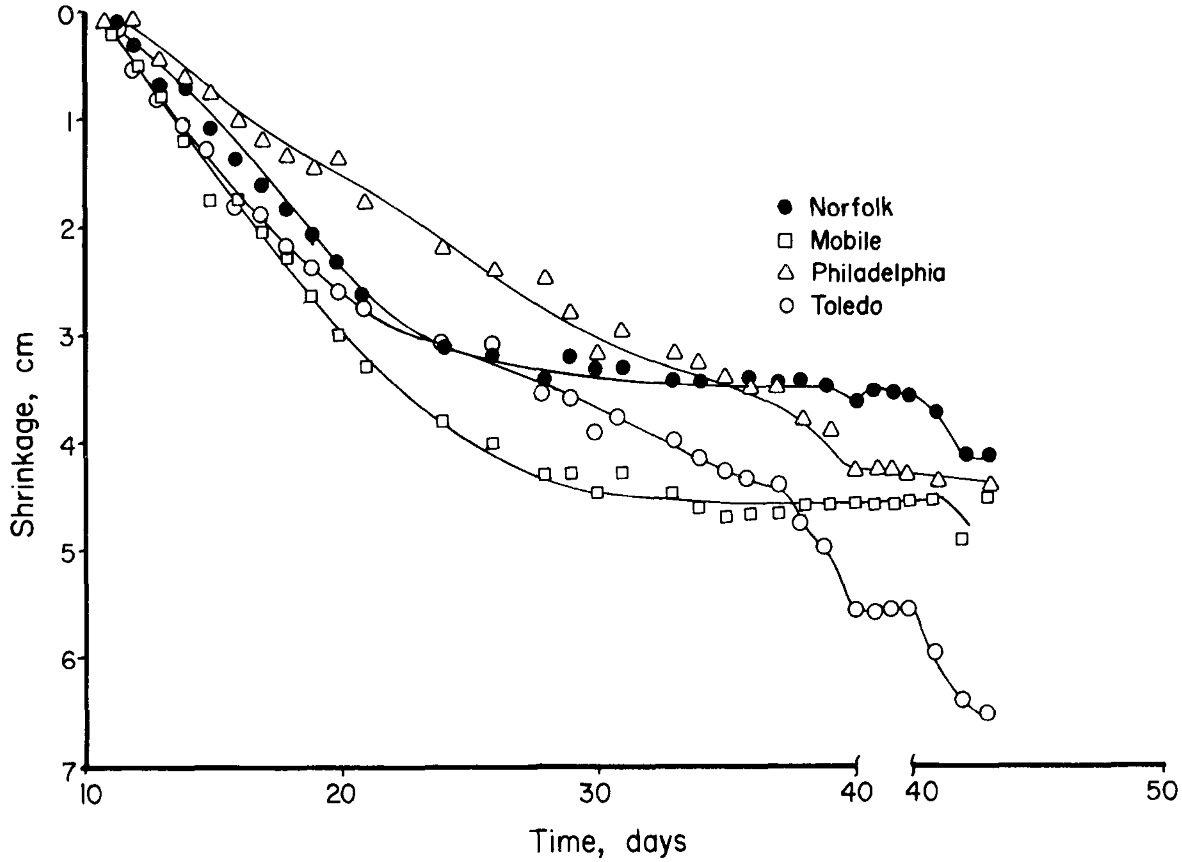

Figure 67. Cumulative shrinkage of the four dredged material samples during Experiment A in the environmental chamber

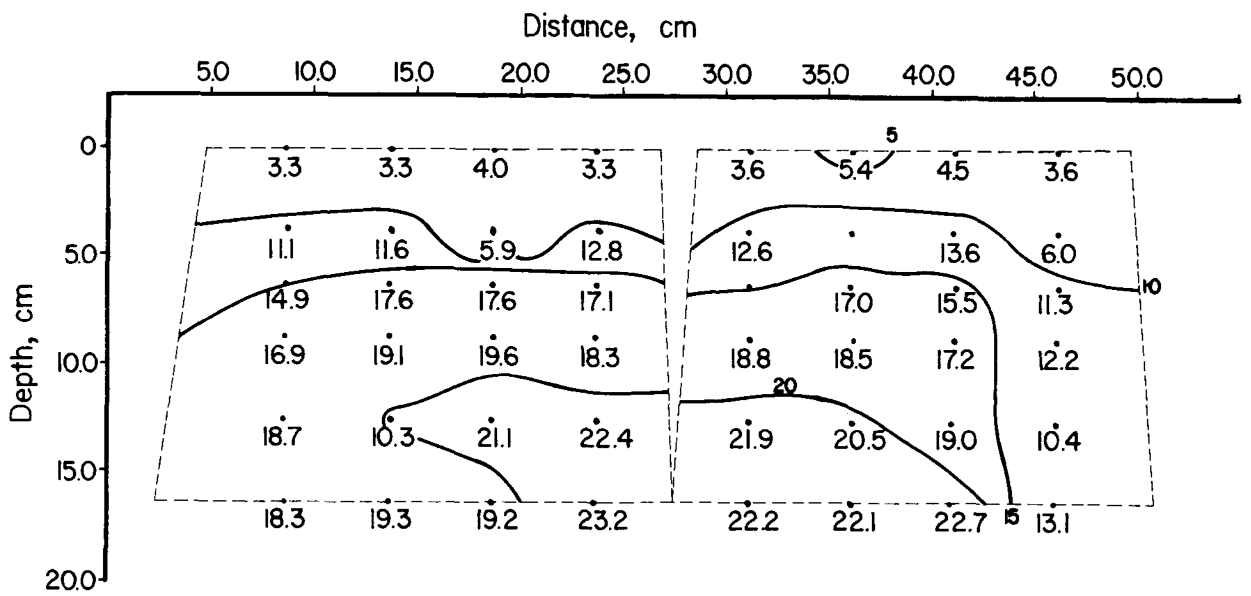

Figure 68. Distribution of the moisture content given in percent by weight for the Philadelphia dredged material from Experiment A dissected 47 days after decantation. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

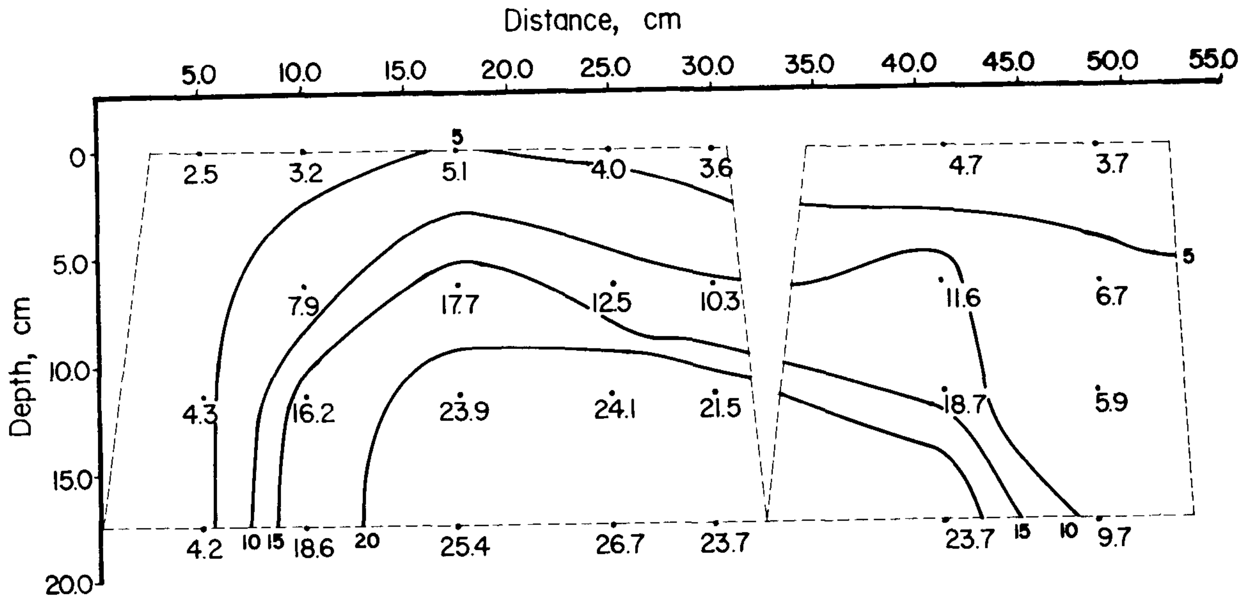

Figure 69. Distribution of the moisture content given in percent by weight for the Toledo dredged material from Experiment A dissected 48 days after decantation. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

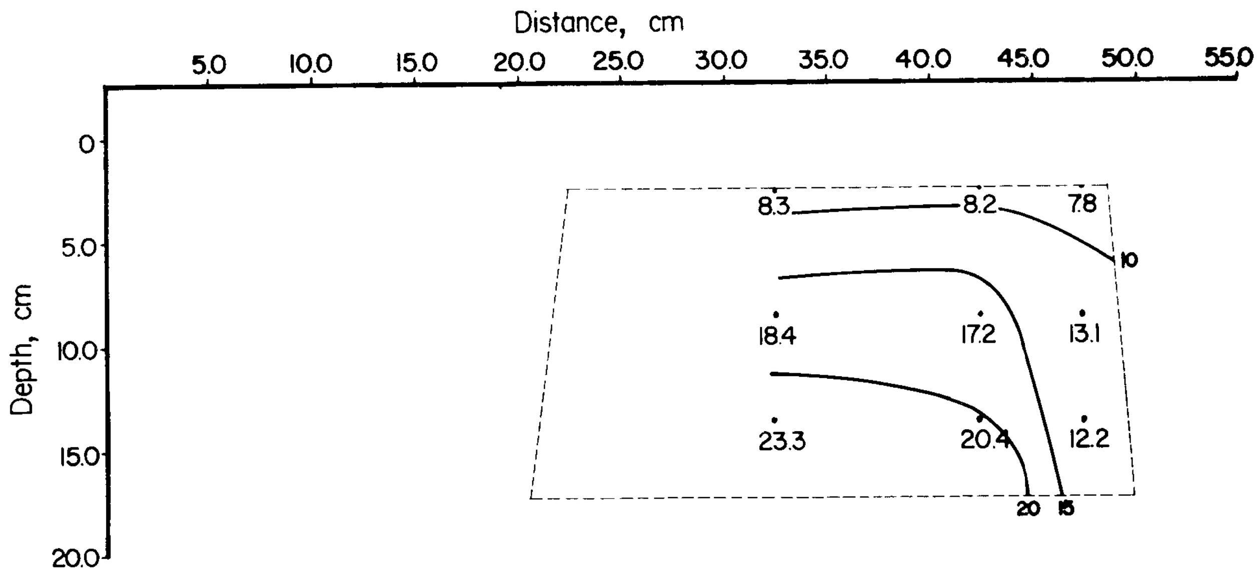

Figure 70. Partial cross section of Toledo material in another direction

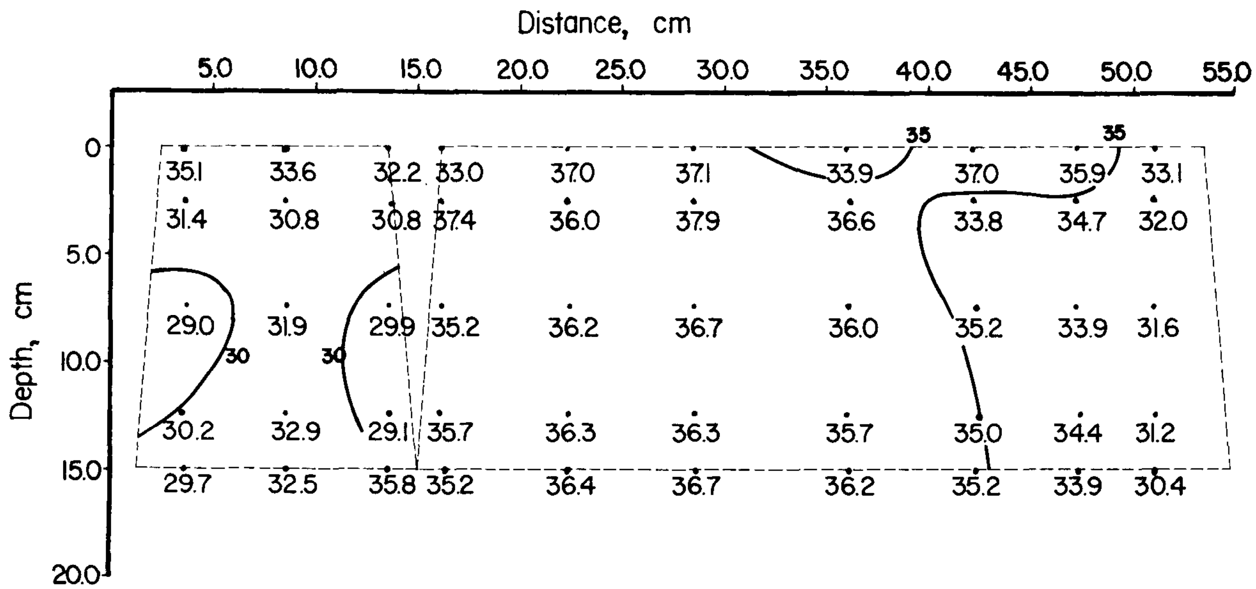

Figure 71. Distribution of the moisture content given in percent by weight for the Norfolk dredged material from Experiment A dissected 48 days after decantation. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

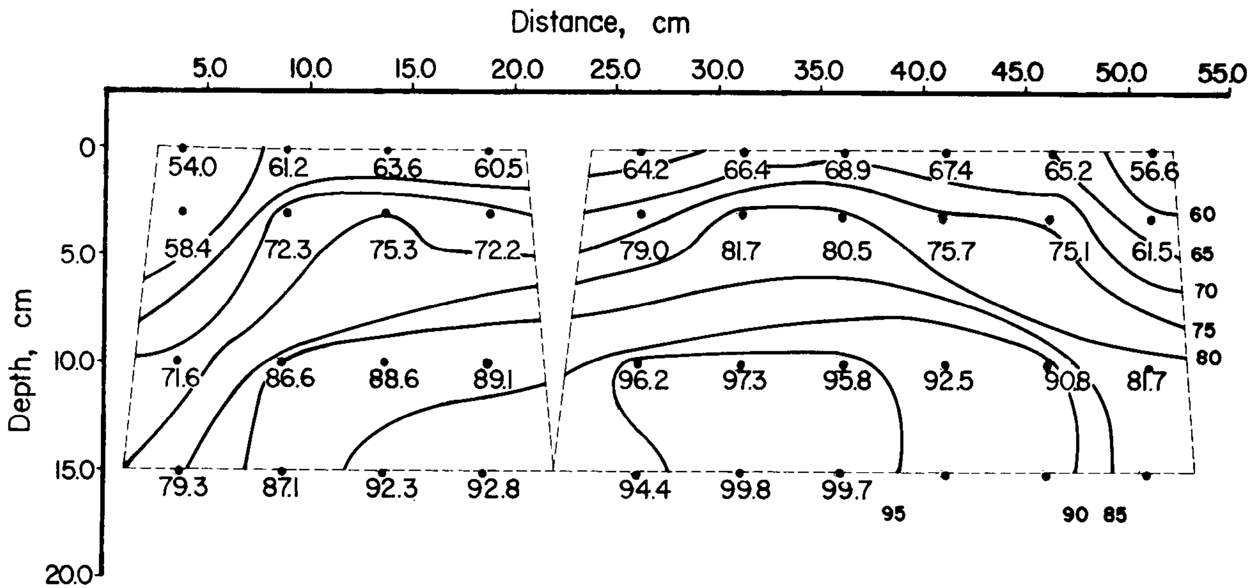

Figure 72. Distribution of the moisture content given in percent by weight for the Mobile dredged material from Experiment A dissected 48 days after decantation. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

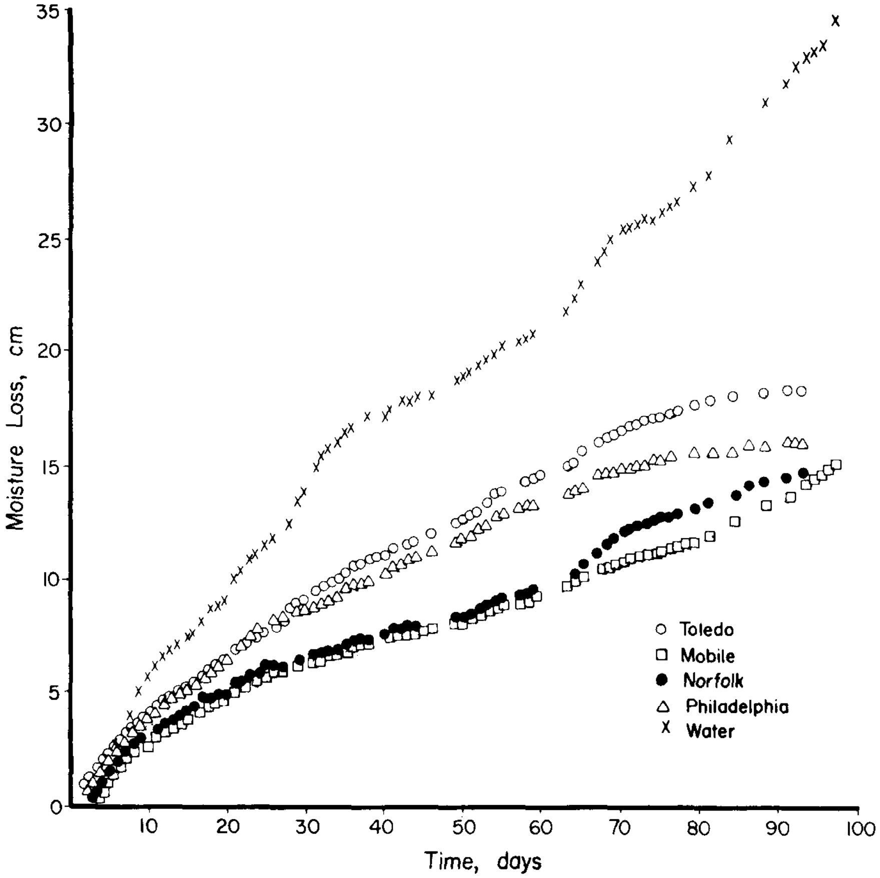

Figure 73. Cumulative water loss from each of the four dredged material samples and the free-water surface during Experiment B in the field

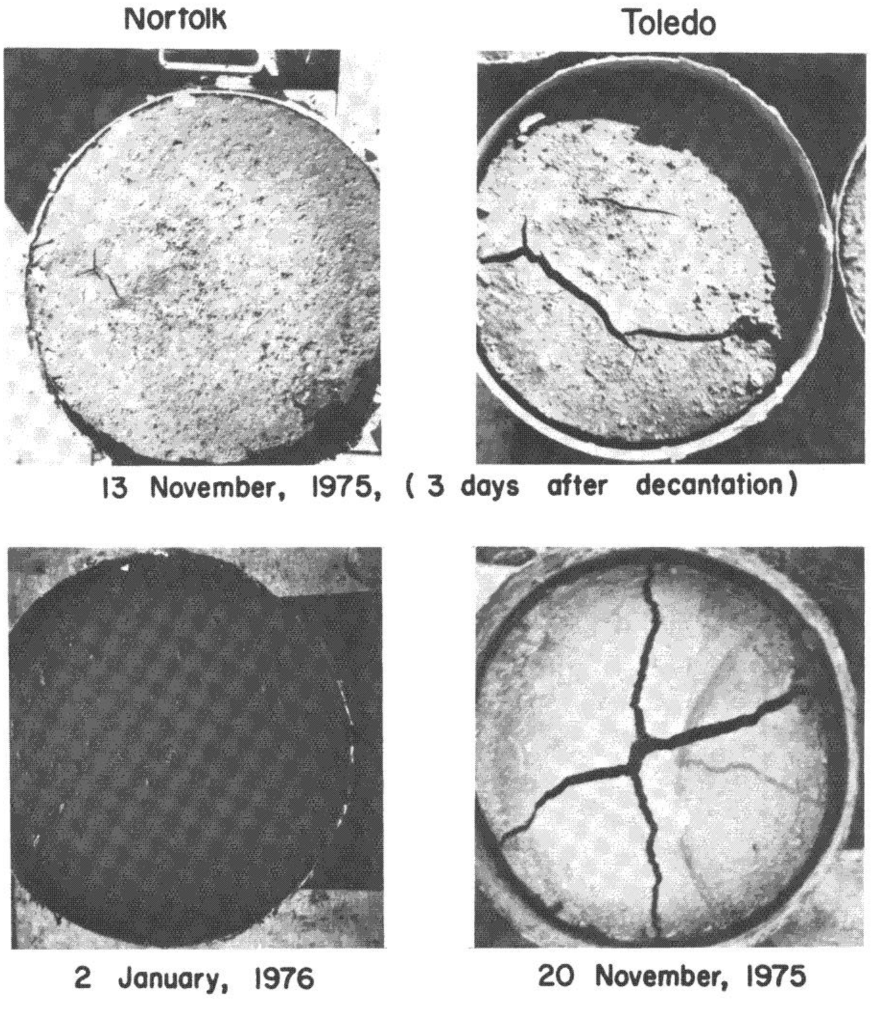

Figure 74. Dredged material from Norfolk and Toledo in various stages of drying

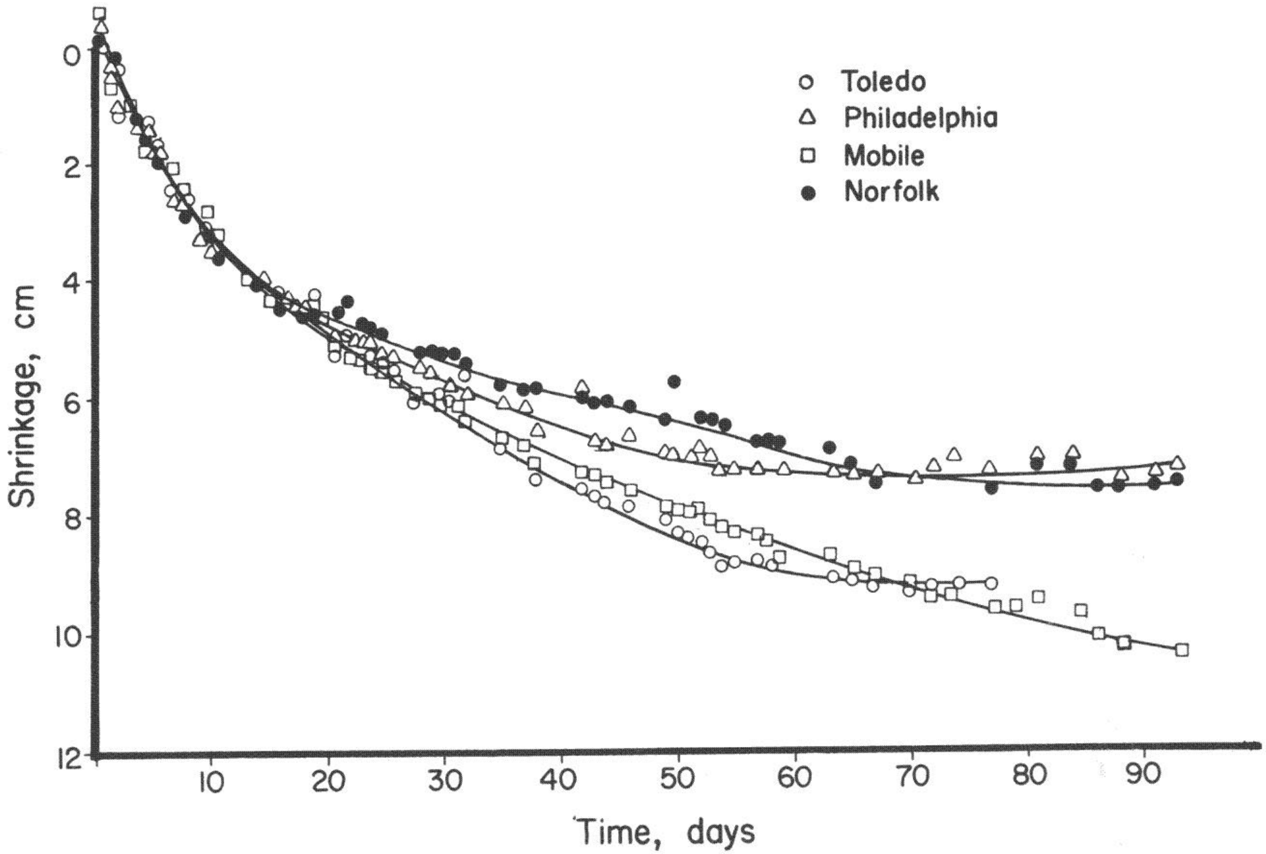

Figure 75. The vertical shrinkage for the four dredged material samples during Experiment B in the field

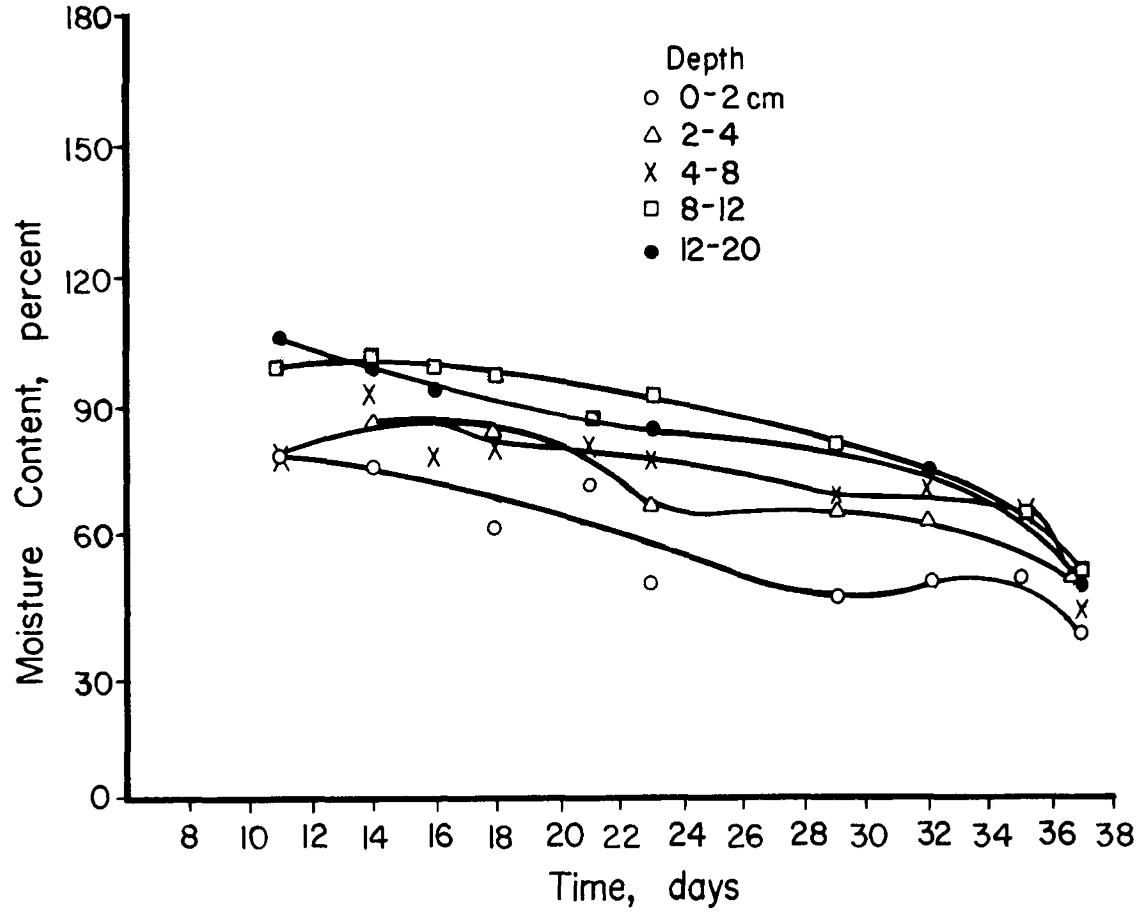

Figure 76. Moisture content profile with depth for the Philadelphia dredged material during Experiment B in the field

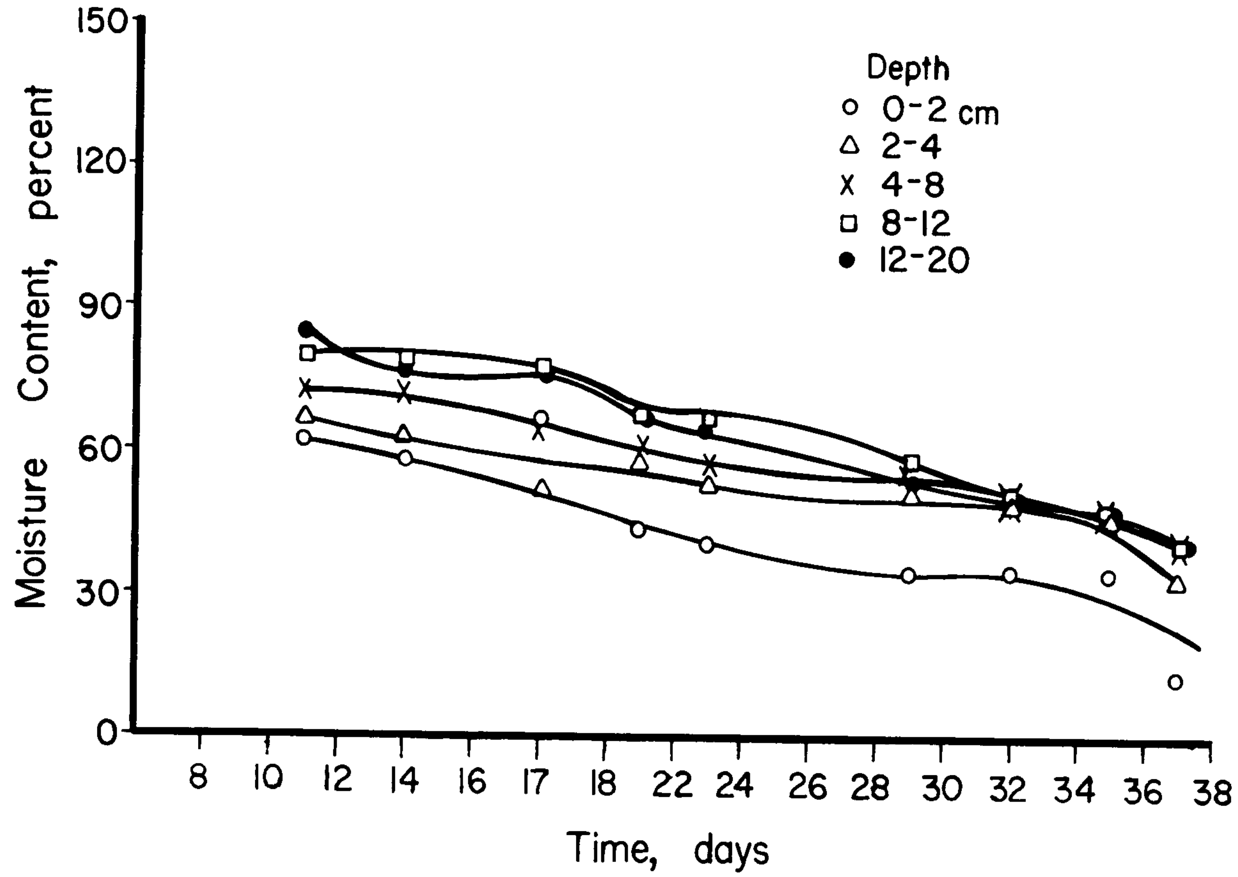

Figure 77. Moisture content profile with depth for the Toledo dredged material during Experiment B in the field

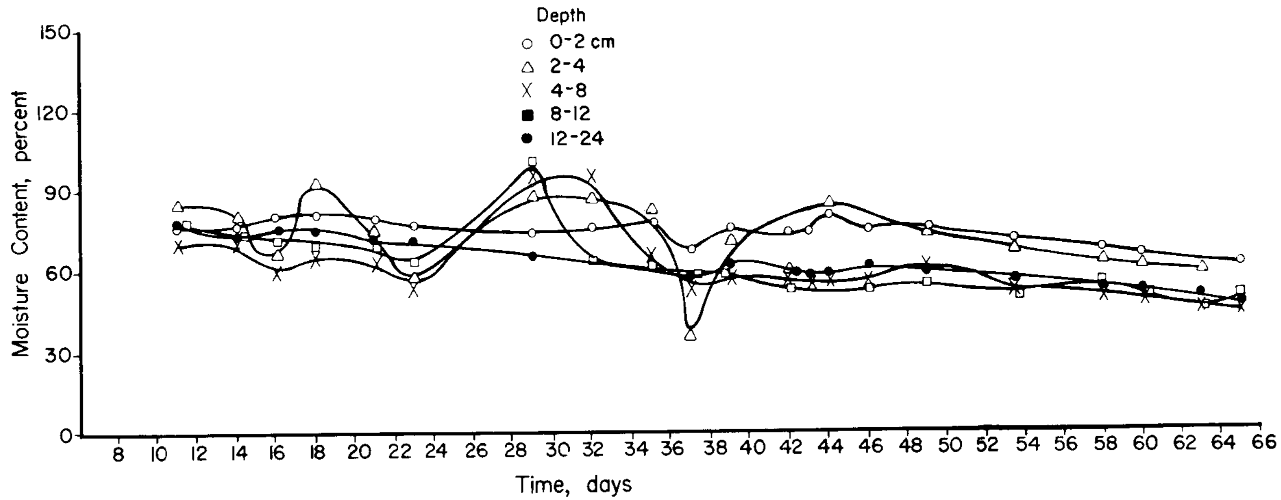

Figure 78. Moisture content profile with depth for the Norfolk dredged material during Experiment B in the field

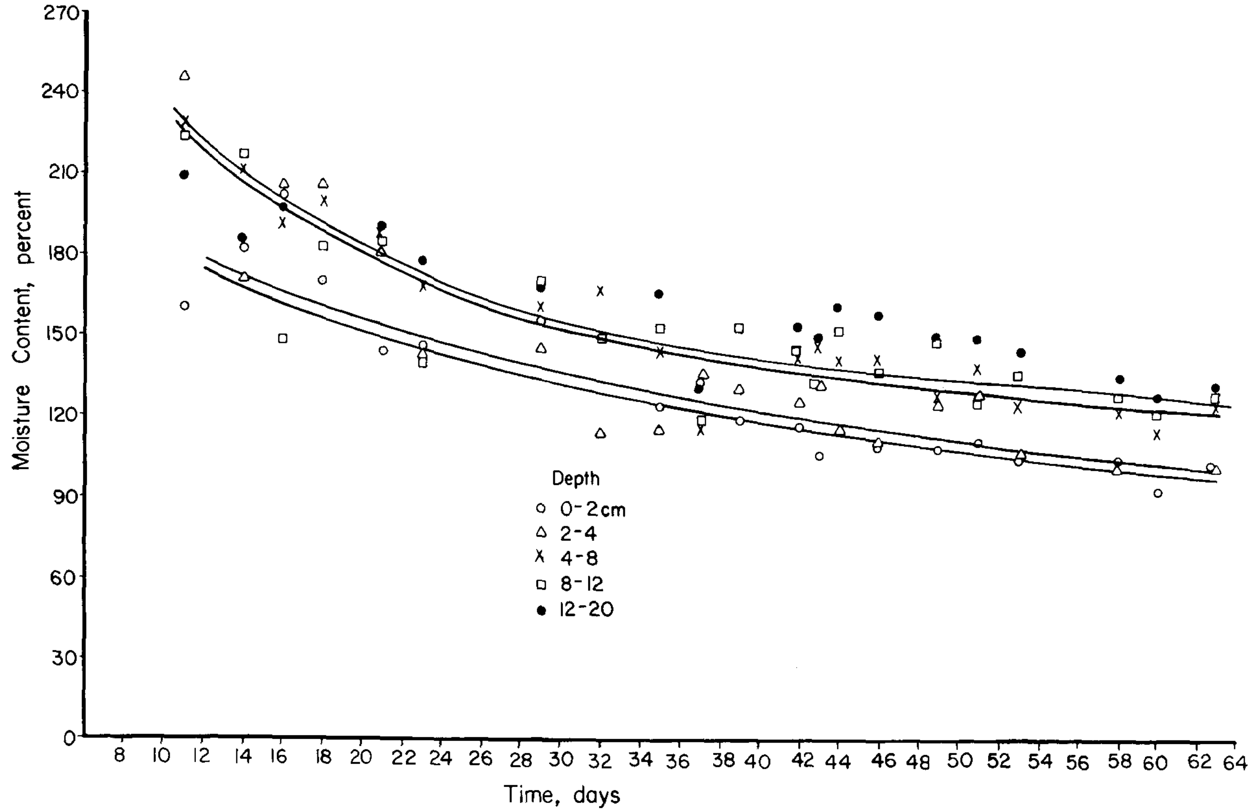

Figure 79. Moisture content profile with depth for the Mobile dredged material during Experiment B in the field

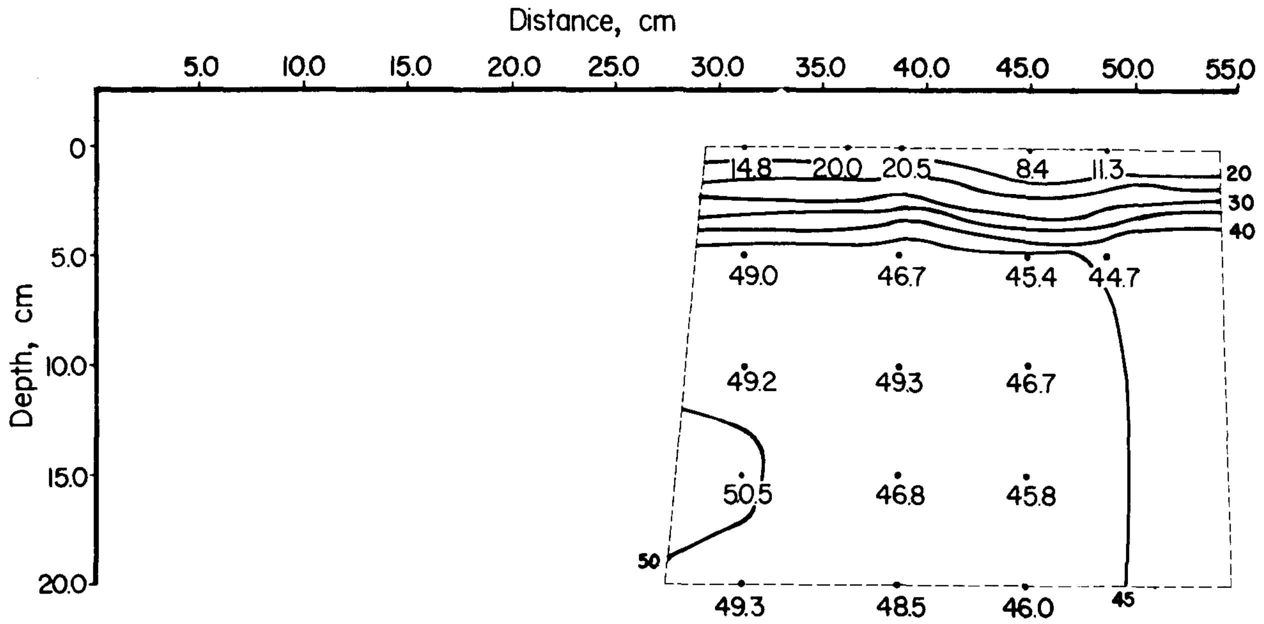

Figure 80. Distribution of the moisture content given in percent by weight for the Philadelphia dredged material from Experiment A dissected 38 days after decantation. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

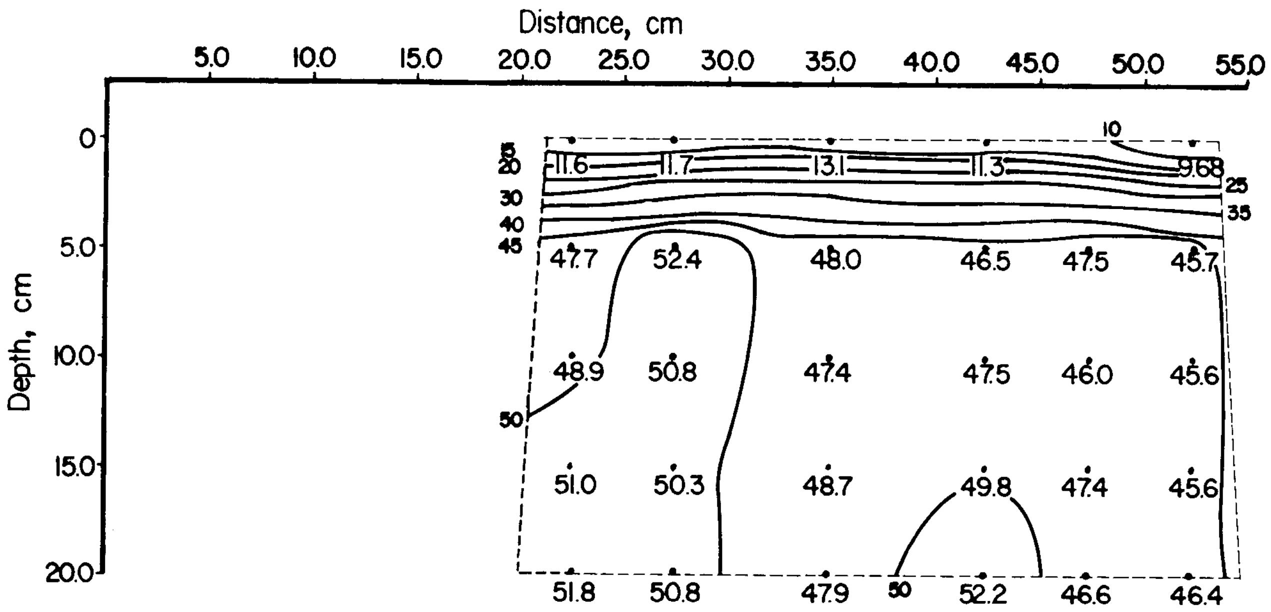

Figure 81. Partial cross section of Philadelphia material in another direction

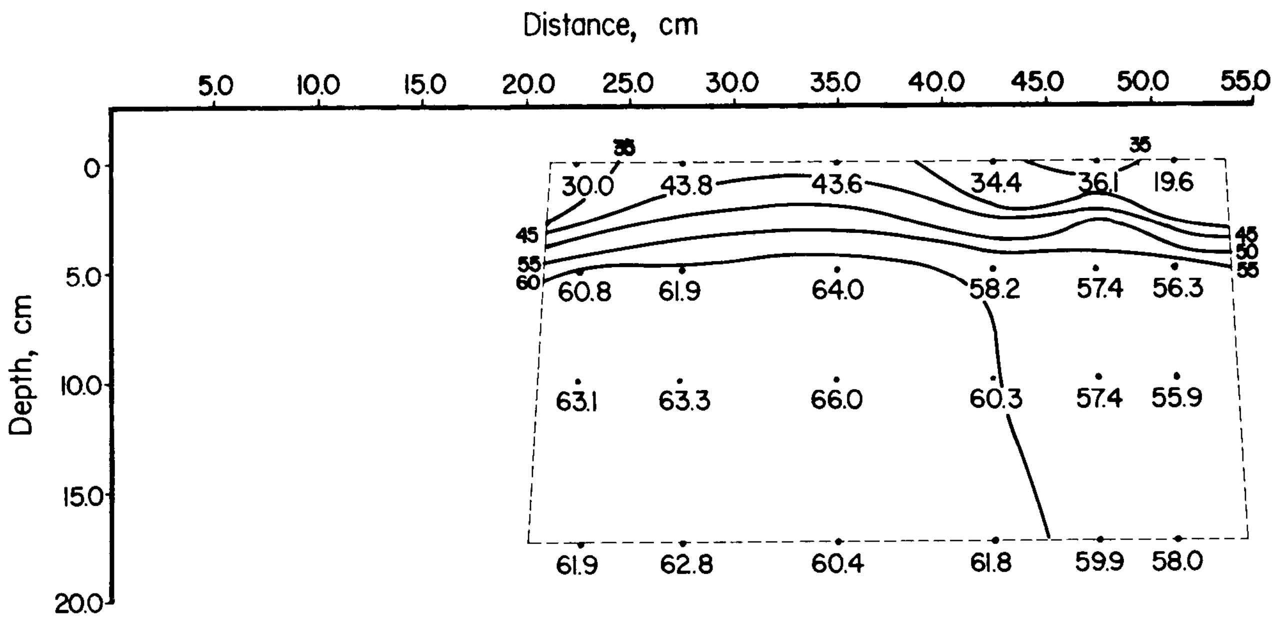

Figure 82. Distribution of the moisture content given in percent by weight for the Toledo dredged material from Experiment A dissected 38 days after decantation. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

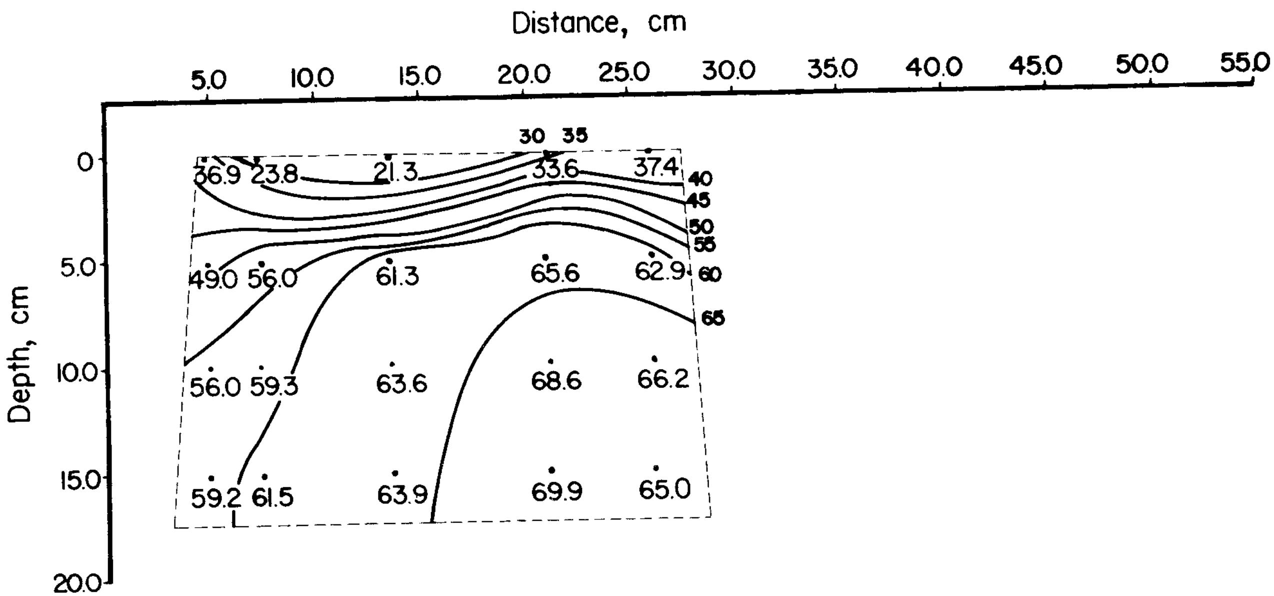

Figure 83. Partial cross section of Toledo material in another direction

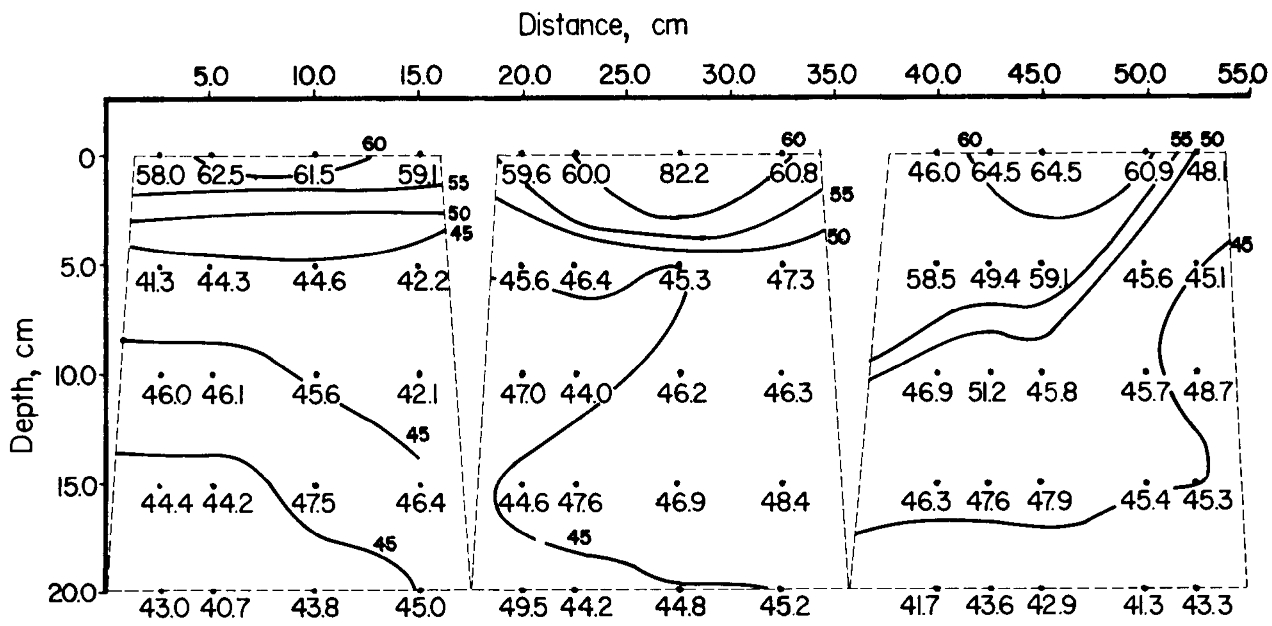

Figure 84. Distribution of the moisture content given in percent by weight for the Norfolk dredged material from Experiment A dissected 54 days after decantation. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

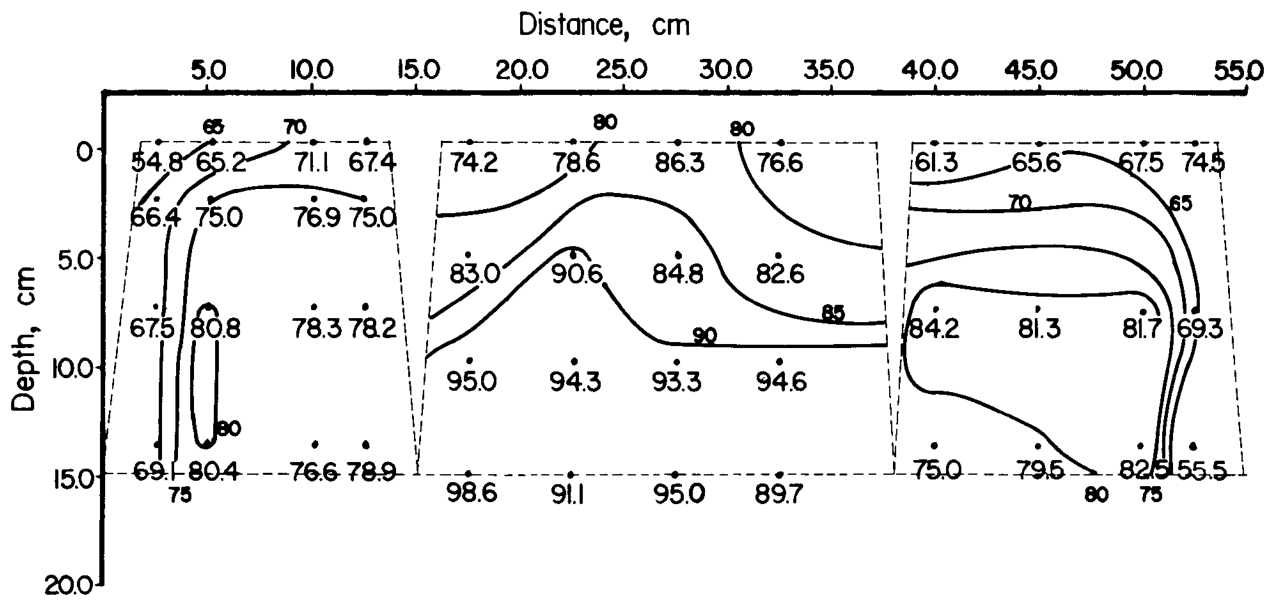

Figure 85. Distribution of the moisture content given in percent by weight for the Mobile dredged material from Experiment A dissected 55 days after decantation. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

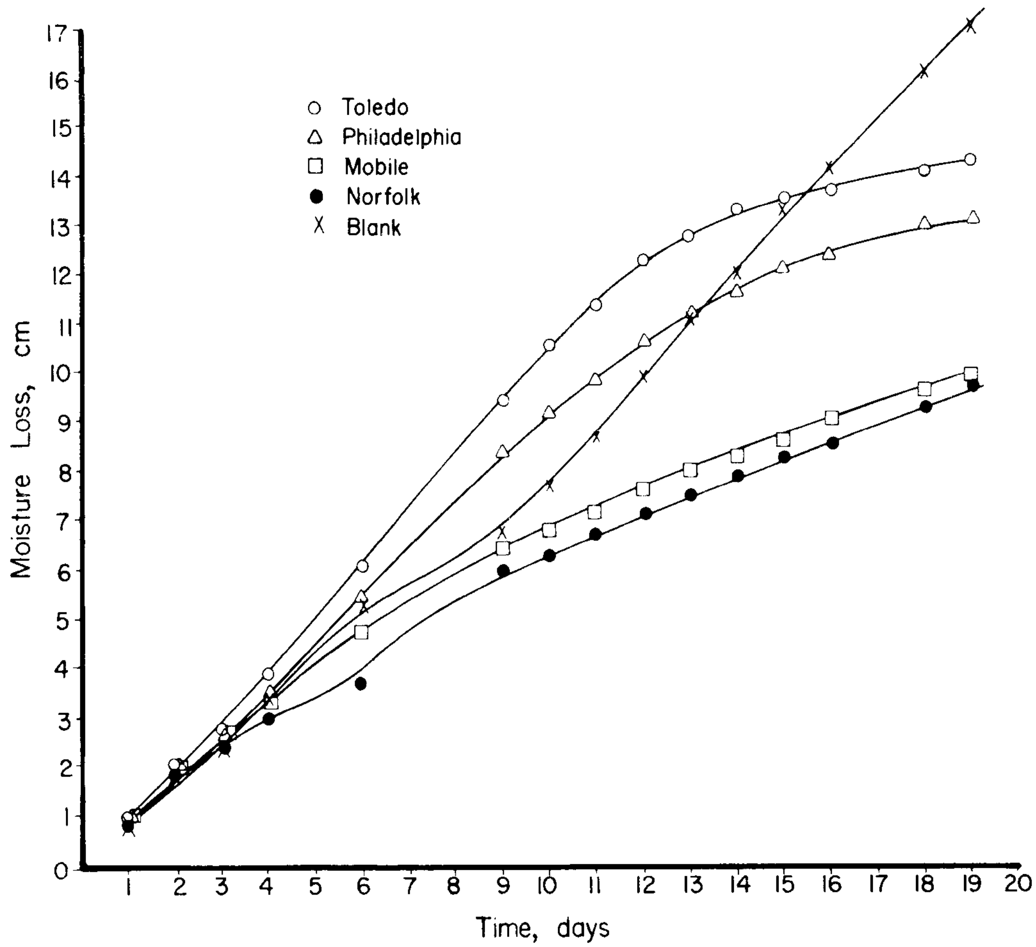

Figure 86. The cumulative loss of water from each of the four dredged material samples during Experiment C in the environmental chamber

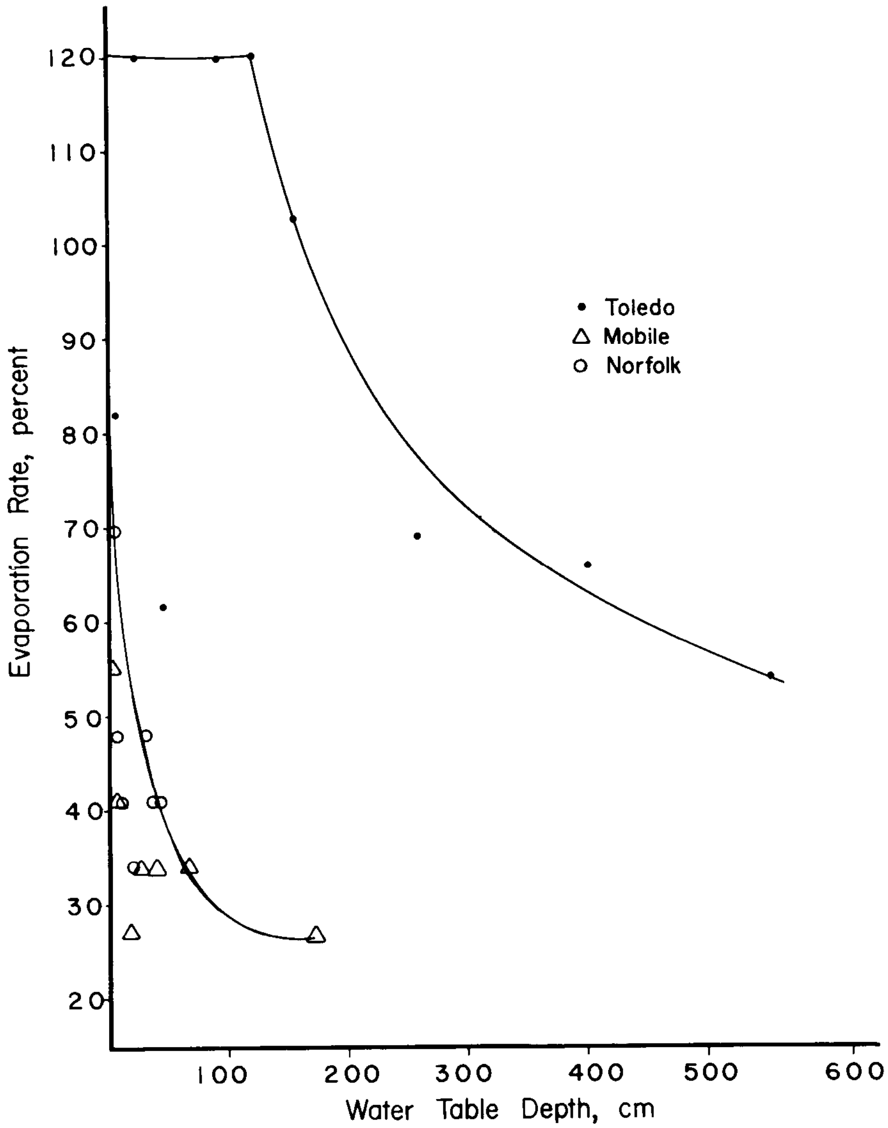

Figure 87. Ratio of evaporation rate as a function of the water table on the samples

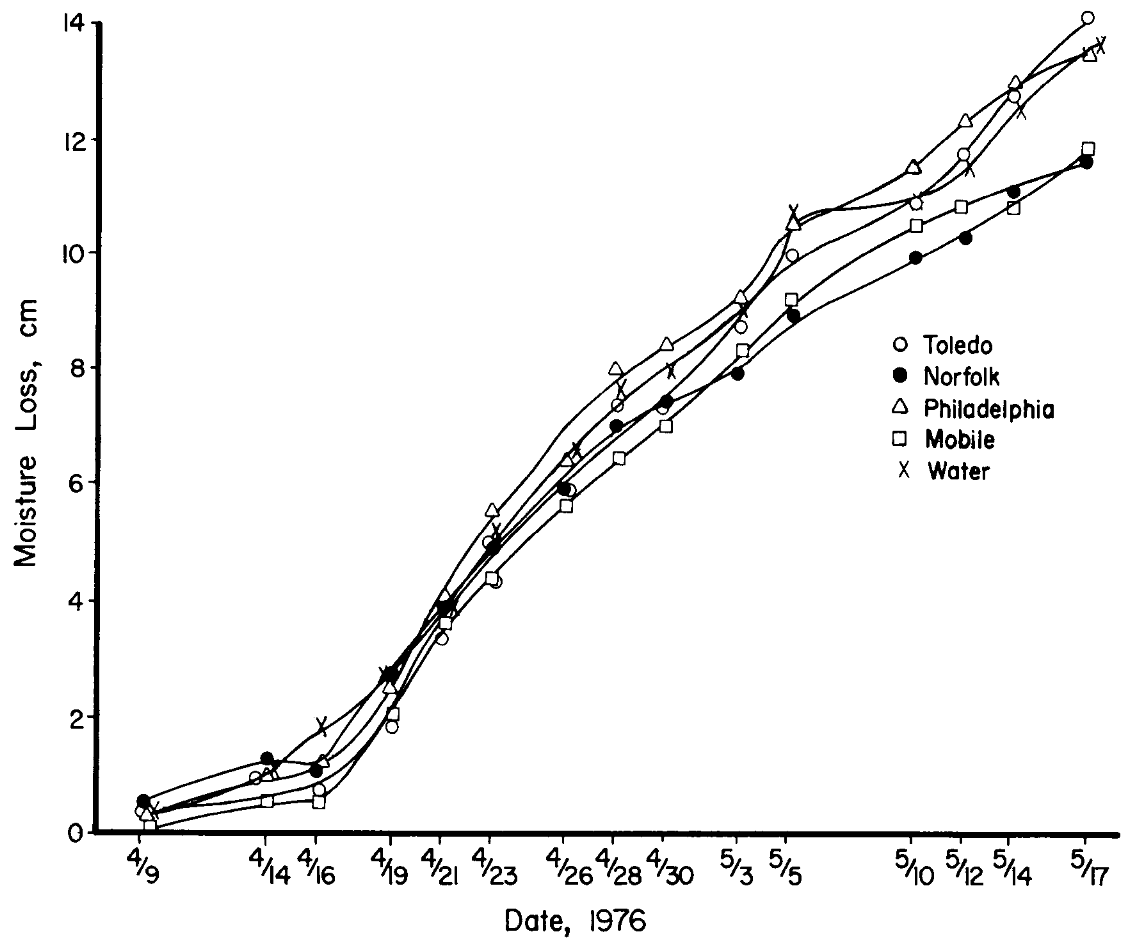

Figure 88. Cumulative water loss from each of the four samples in deep containers with drains and from the free-water surface in the field, Experiment D

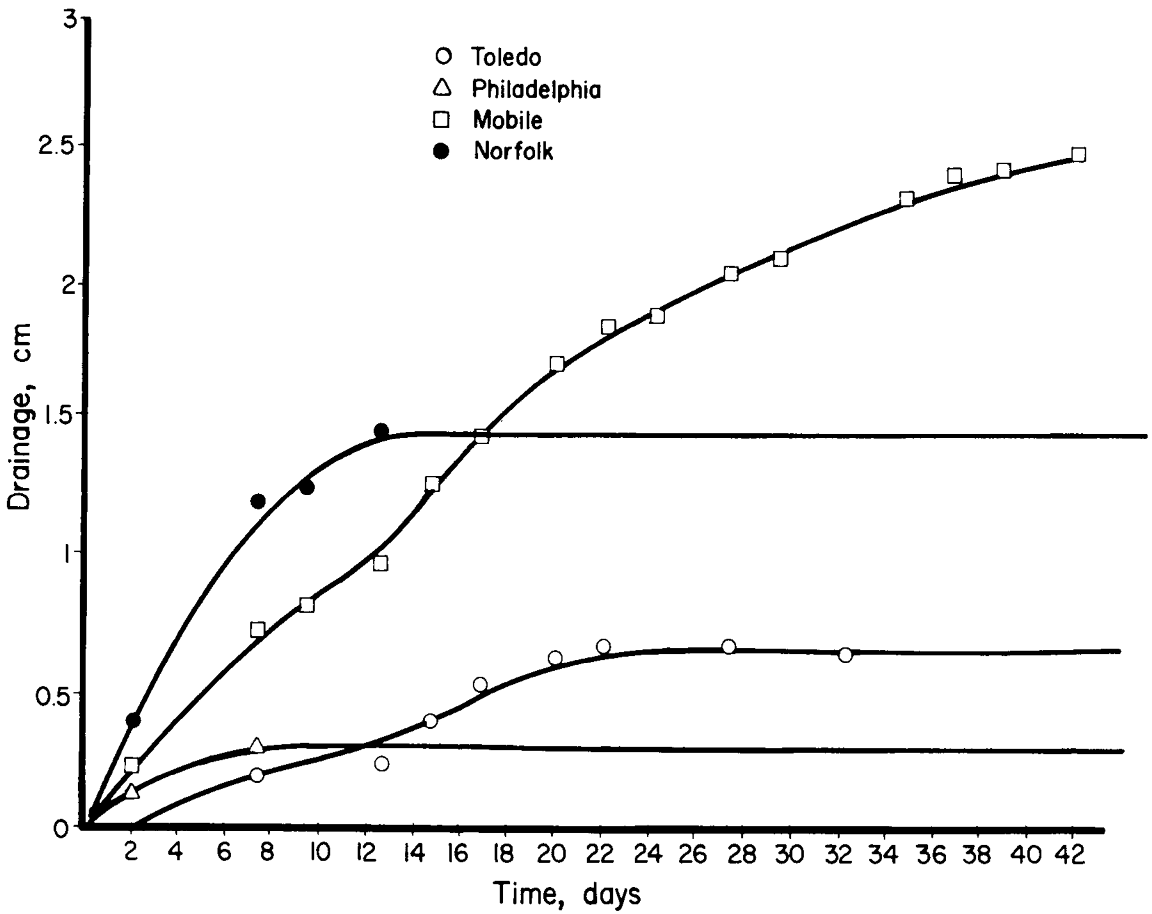

Figure 89. Cumulative water loss through the drains of each of the four samples in deep containers with drains used in Experiment D in the field

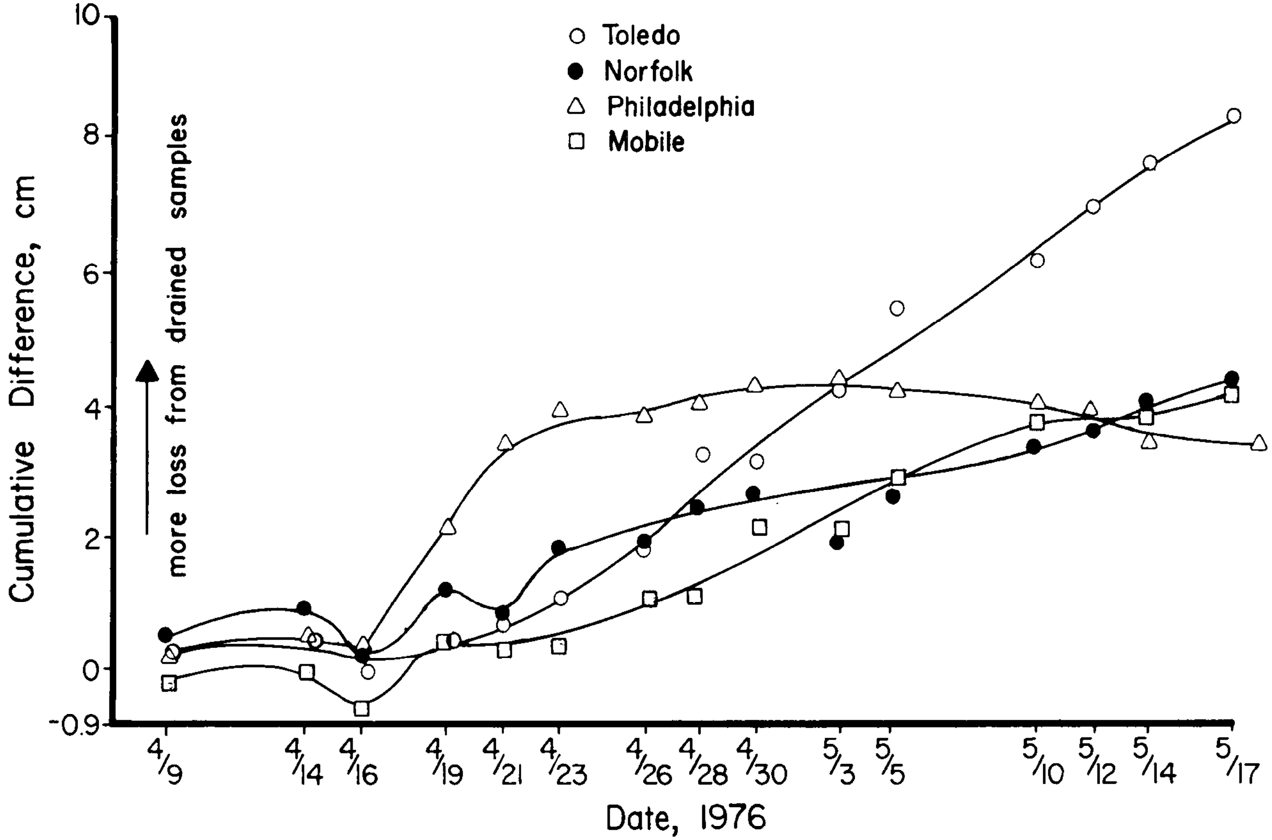

Figure 90. The cumulative difference in total water loss between the deep containers with a drain and those without a drain for each of the four dredged material samples used in Experiment D in the field

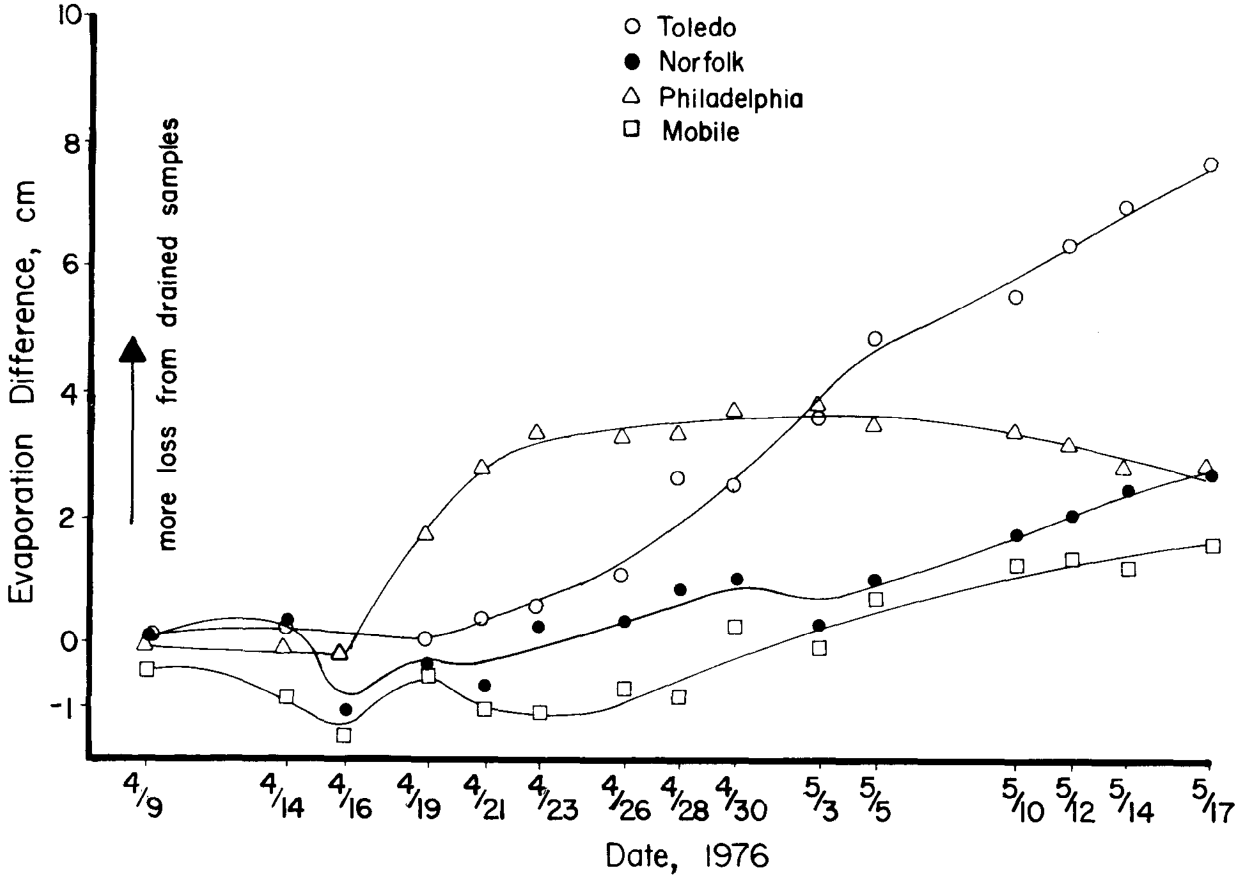

Figure 91. The cumulative difference of water loss due to evaporation from the deep containers with and without drains of each of the four dredged material samples in Experiment D in the field

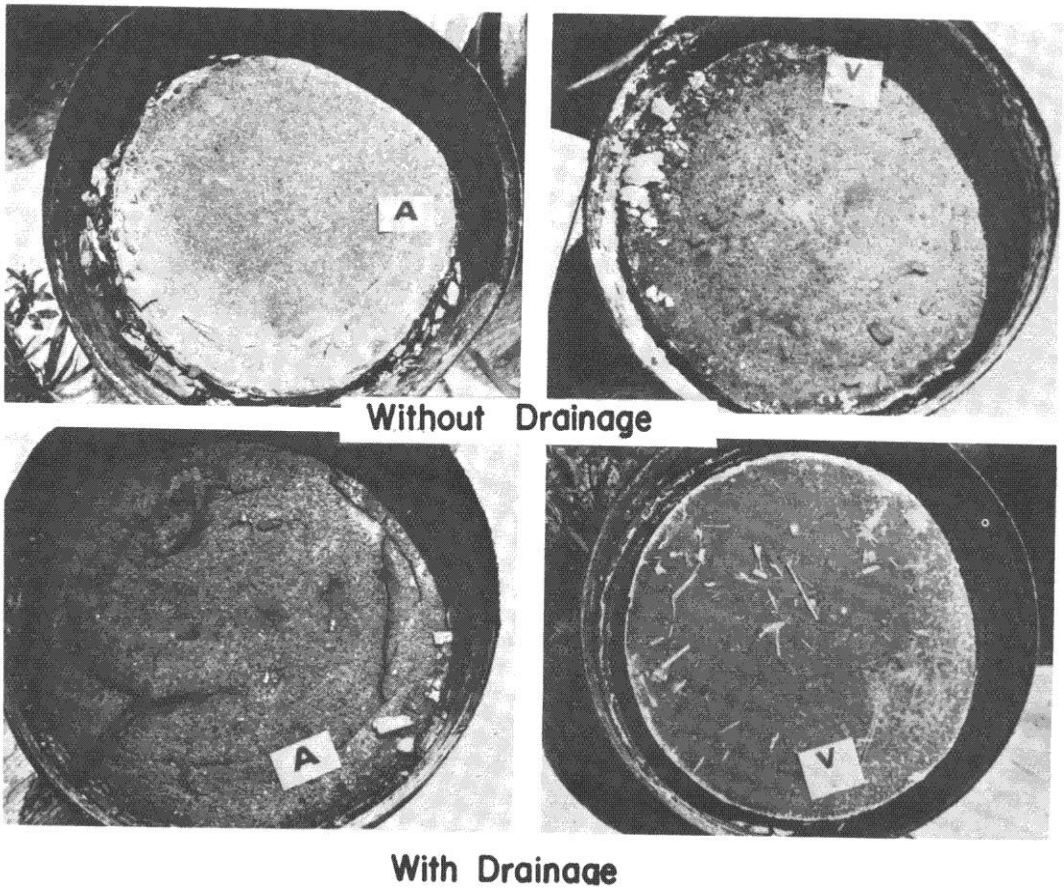

Figure 92. Containers of dredged material from Norfolk (V) and Mobile (A) after 55 days of drying

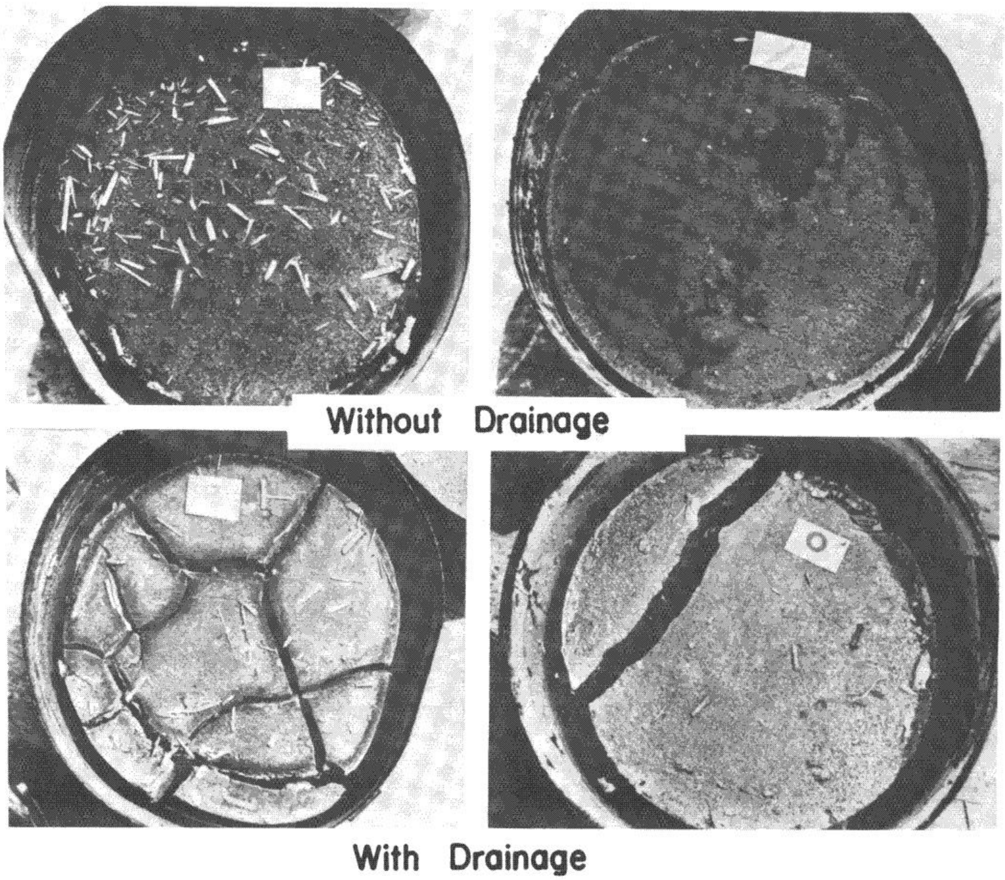

Figure 93. Containers of dredged material from Philadelphia (P) and Toledo (O) after 55 days of drying

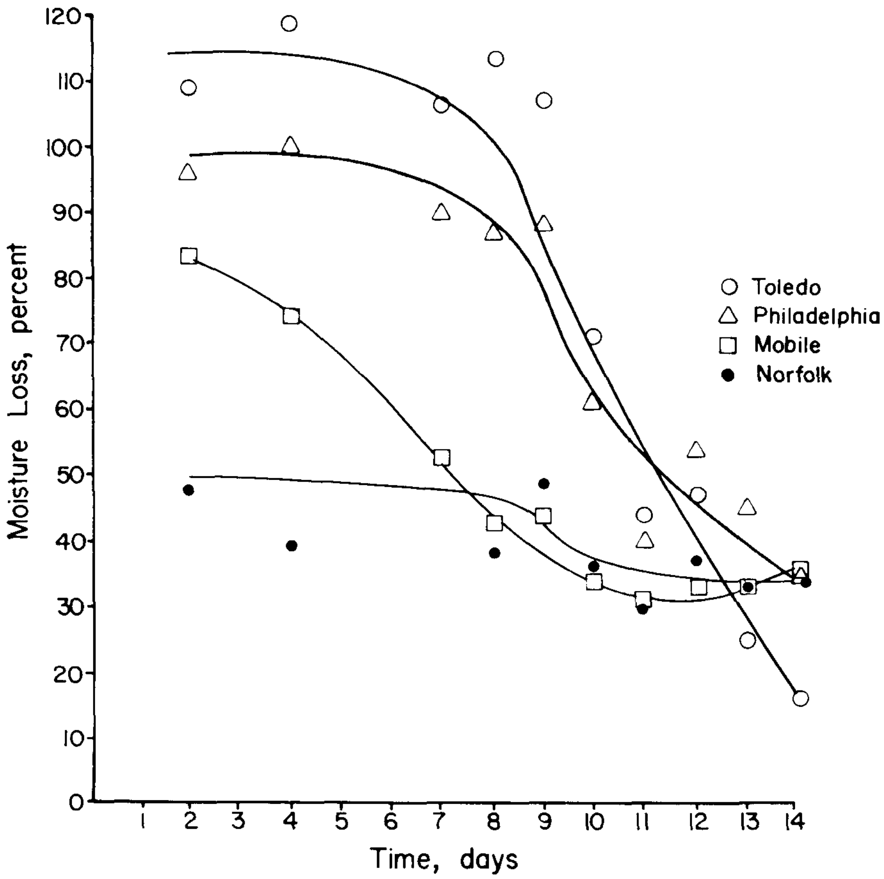

Figure 94. The loss of water from the four samples as a percentage of that from the free-water surface during Experiment B in the environmental chamber

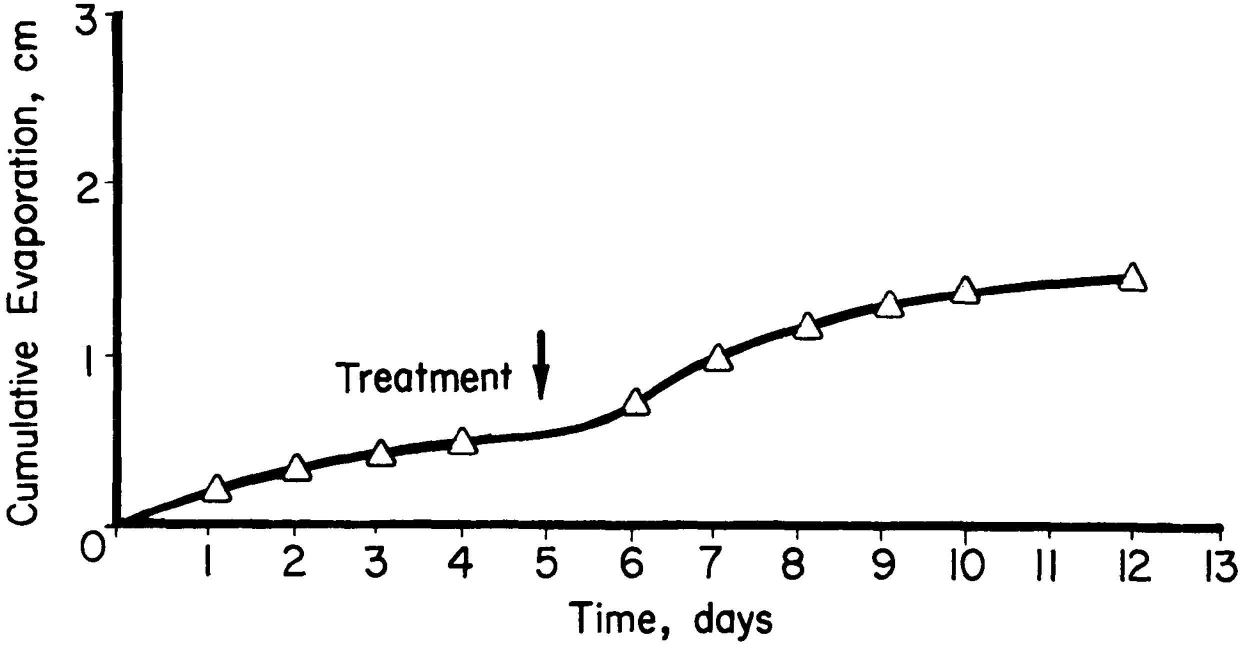

Figure 95. The cumulative water loss from the Philadelphia dredged material in Experiment B in the field before and after removal of a thin layer of crust on day 5

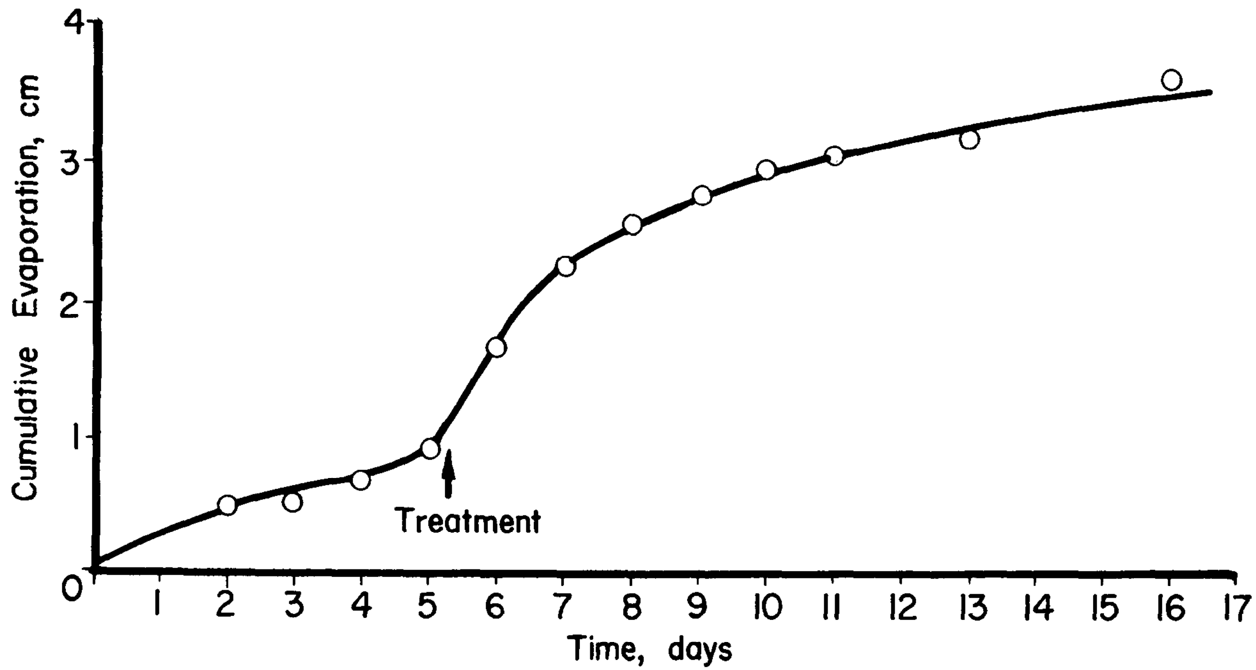

Figure 96. The cumulative water loss from the Toledo dredged material in Experiment B in the field before and after removal of a thin layer of crust on day 5

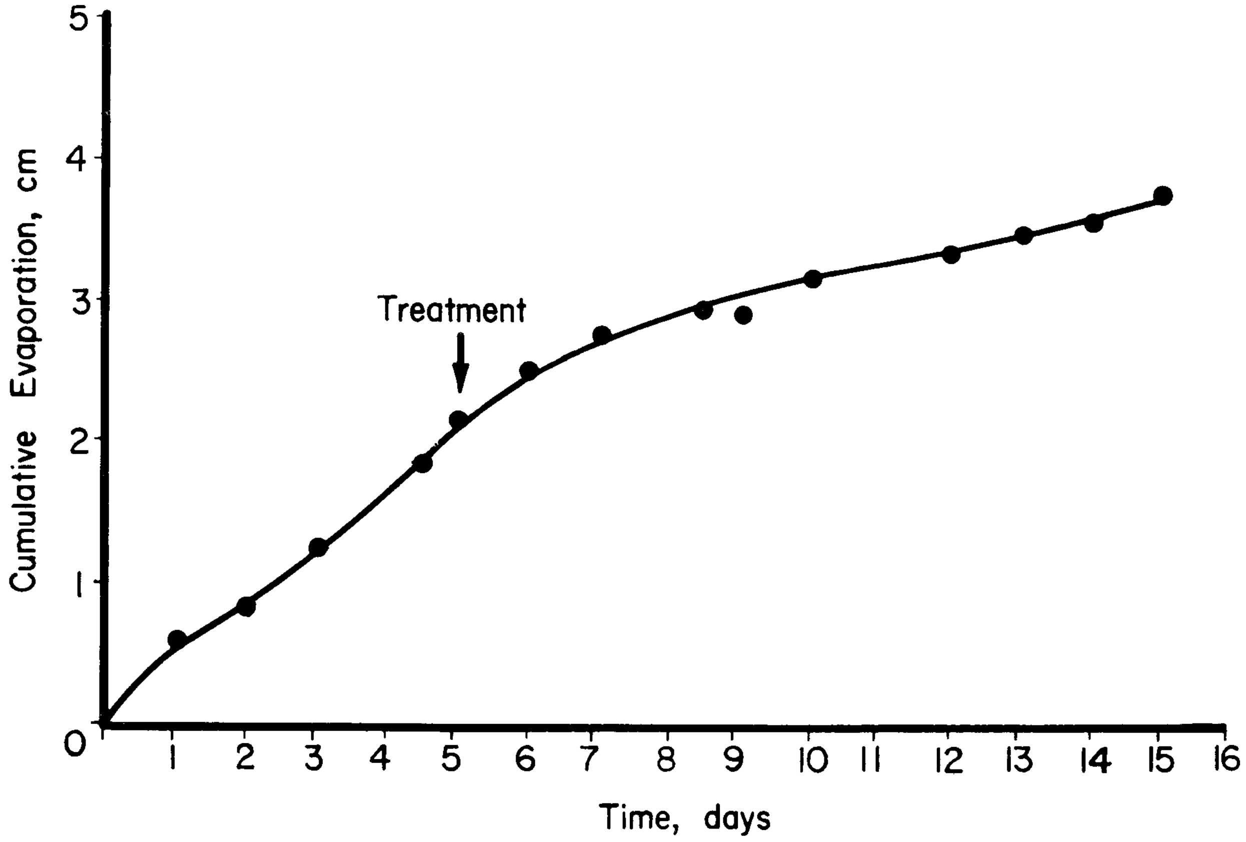

Figure 97. The cumulative water loss from the Norfolk dredged material in Experiment B in the field before and after removal of a thin layer of crust on day 5

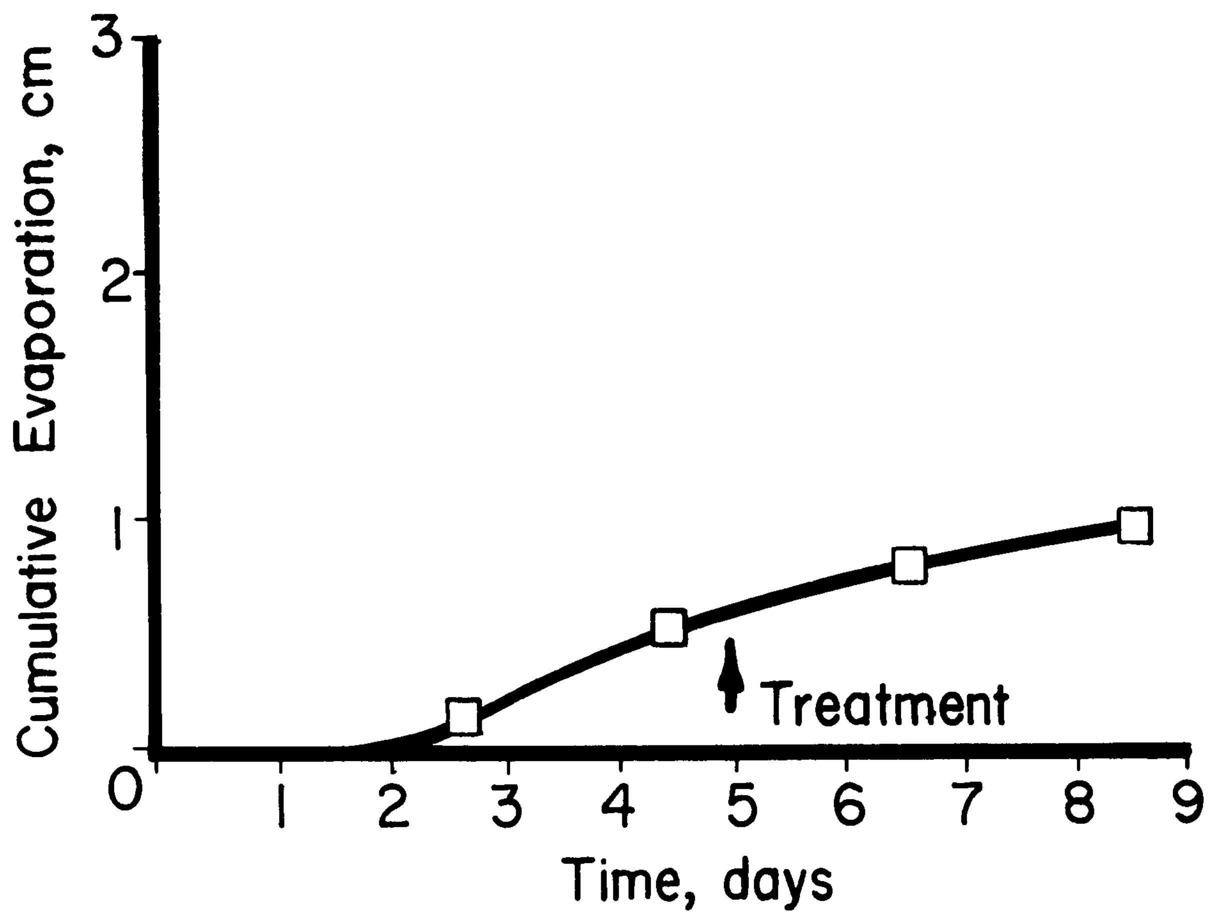

Figure 98. The cumulative water loss from the Mobile dredged material in Experiment B in the field before and after removal of a thin layer of crust on day 5

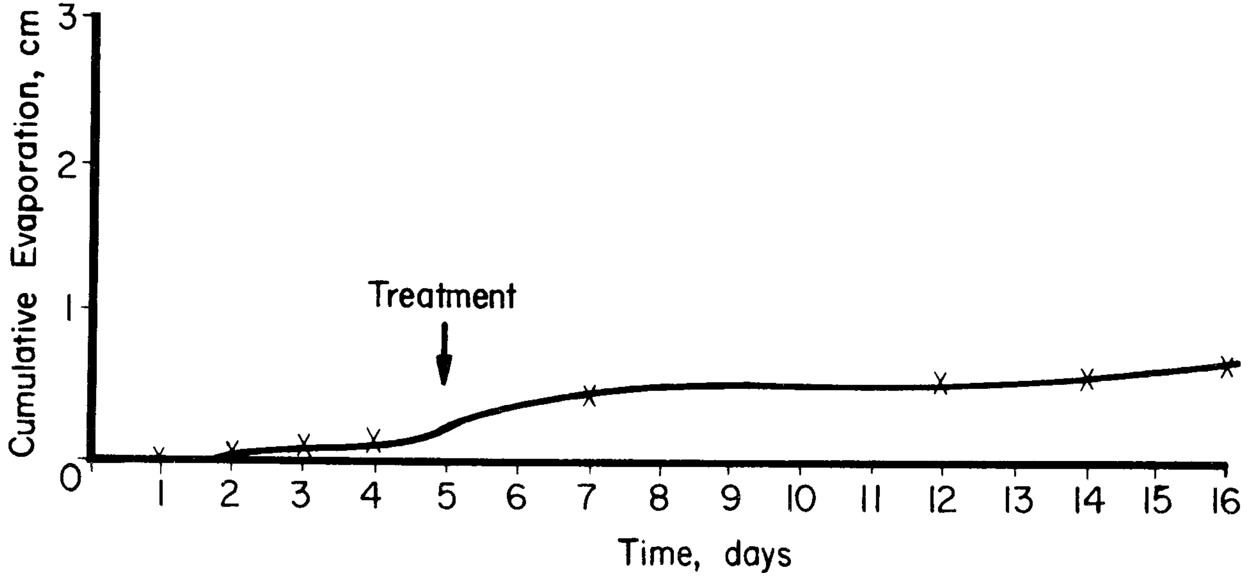

Figure 99. Cumulative evaporation immediately before and after mixing of Philadelphia dredged material in Experiment B in the field

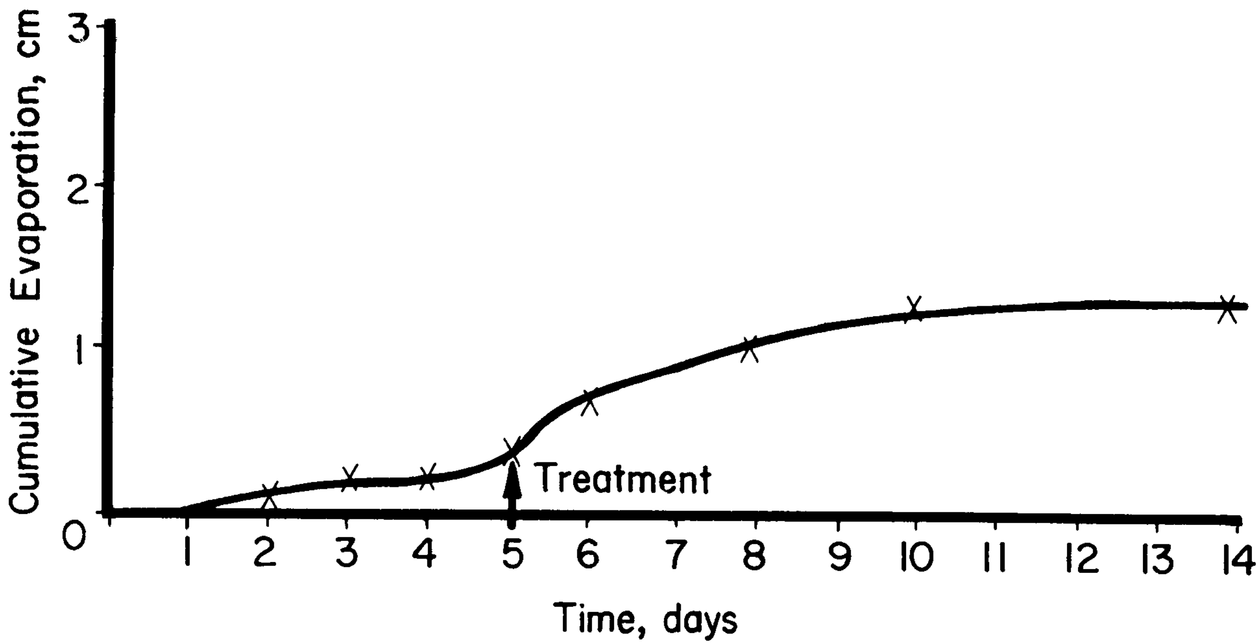

Figure 100. Cumulative evaporation immediately before and after mixing of Toledo dredged material in Experiment B in the field

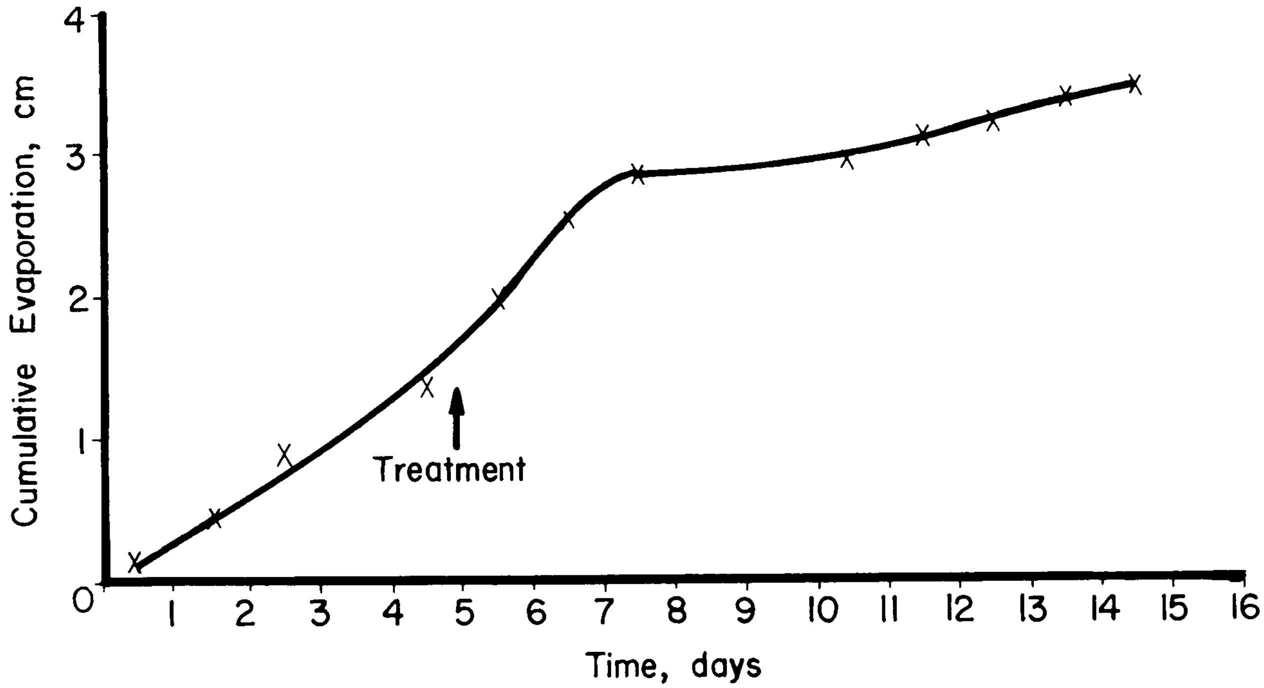

Figure 101. Cumulative evaporation immediately before and after mixing of Norfolk dredged material in Experiment B in the field

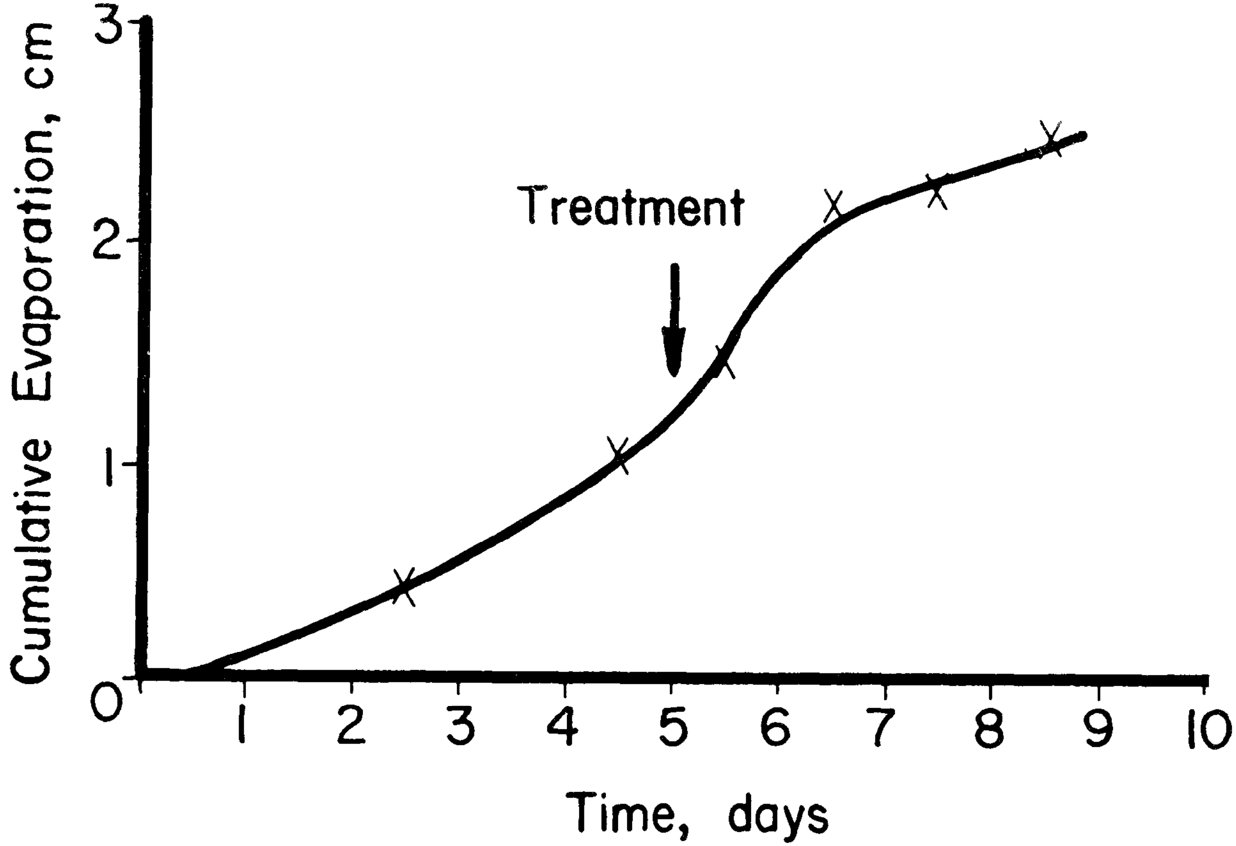

Figure 102. Cumulative evaporation immediately before and after mixing of Mobile dredged material in Experiment B in the field

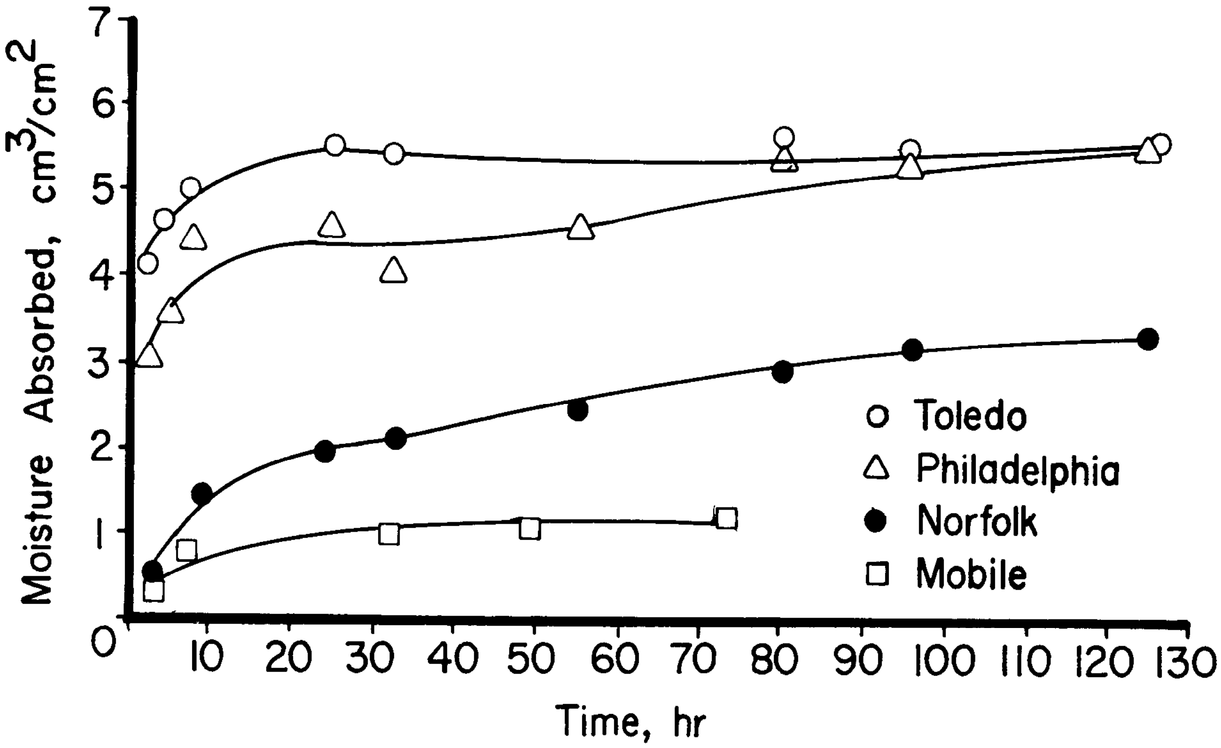

Figure 103. Water absorbed by each of the four initially dry dredged material samples during continuous flooding

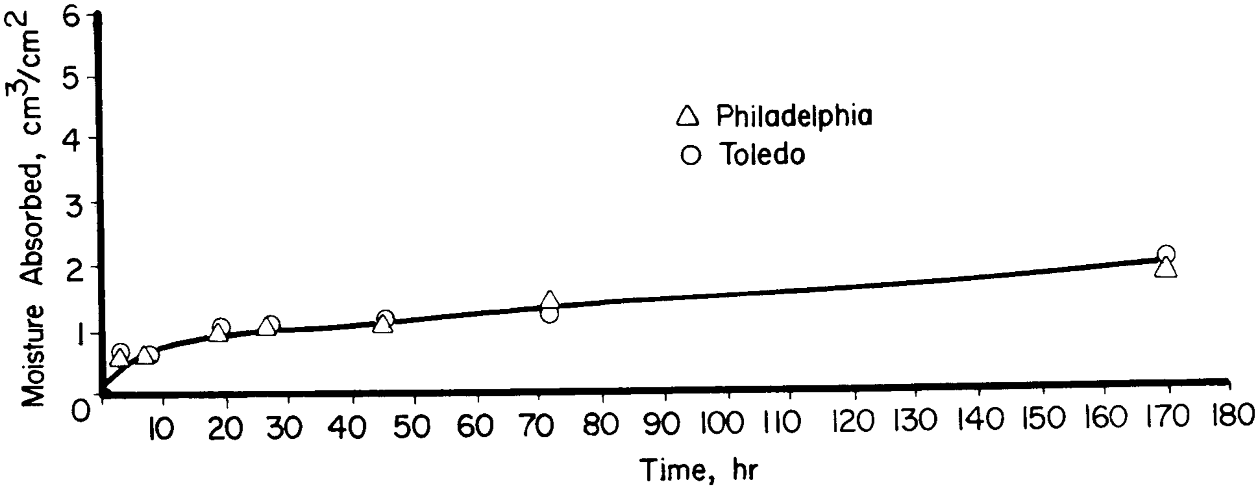

Figure 104. Water absorbed by each of two initially wet dredged material samples during continuous flooding

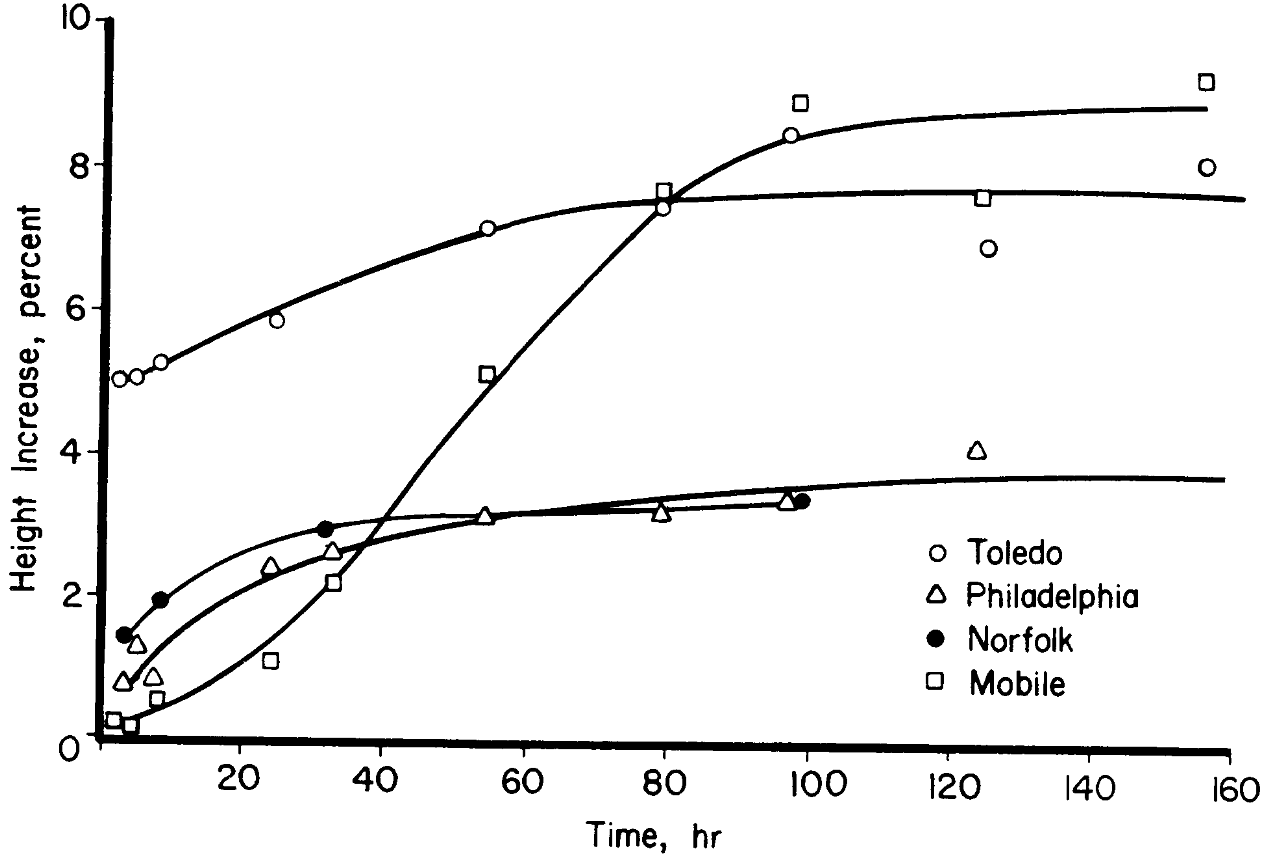

Figure 105. Percent increase in height of each of four initially dry dredged material samples during continuous flooding

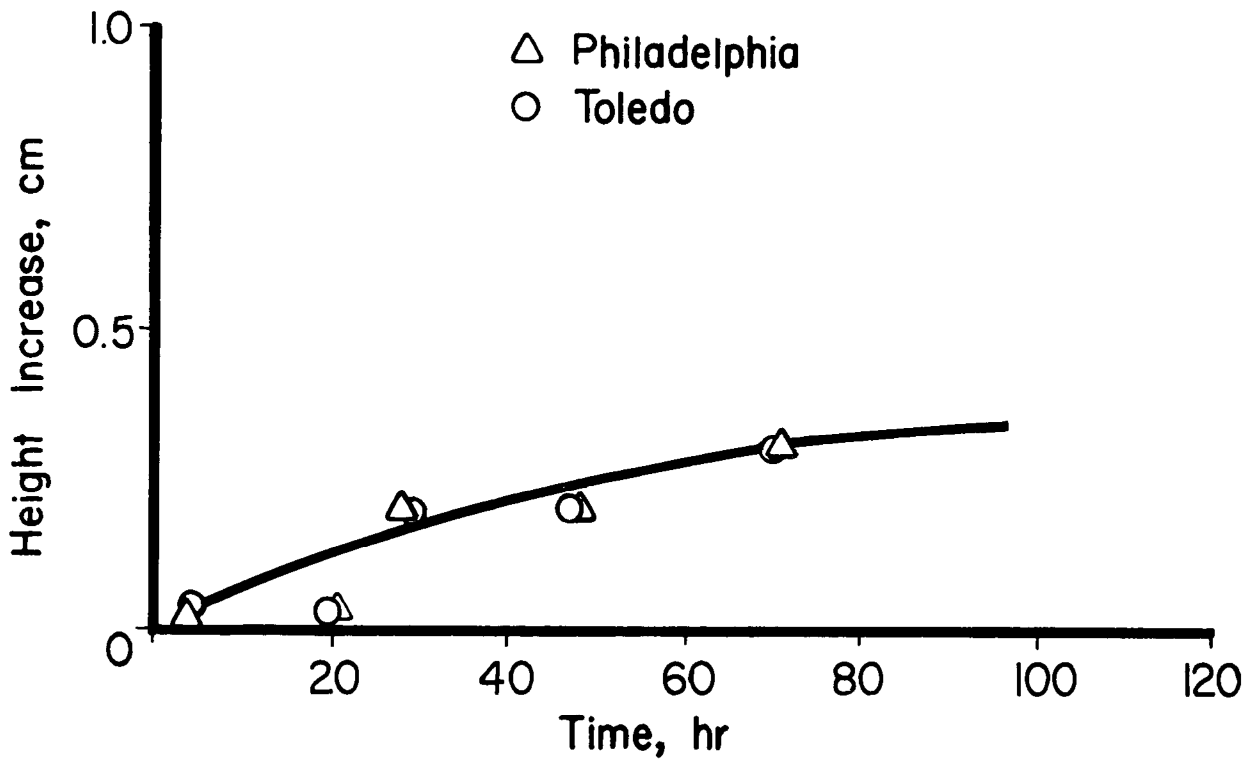

Figure 106. Actual increase in height of each of two initially wet dredged material samples during continuous flooding

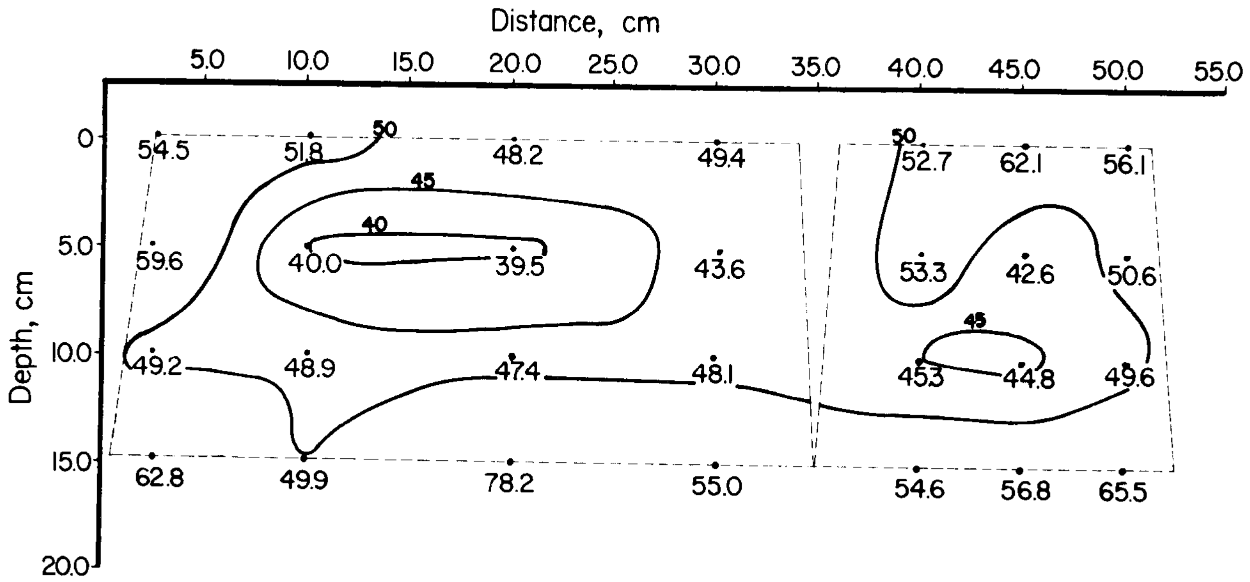

Figure 107. Distribution of the moisture content given in percent by weight for the initially dry Philadelphia dredged material from Experiment B dissected 152 hrs after the application of water. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

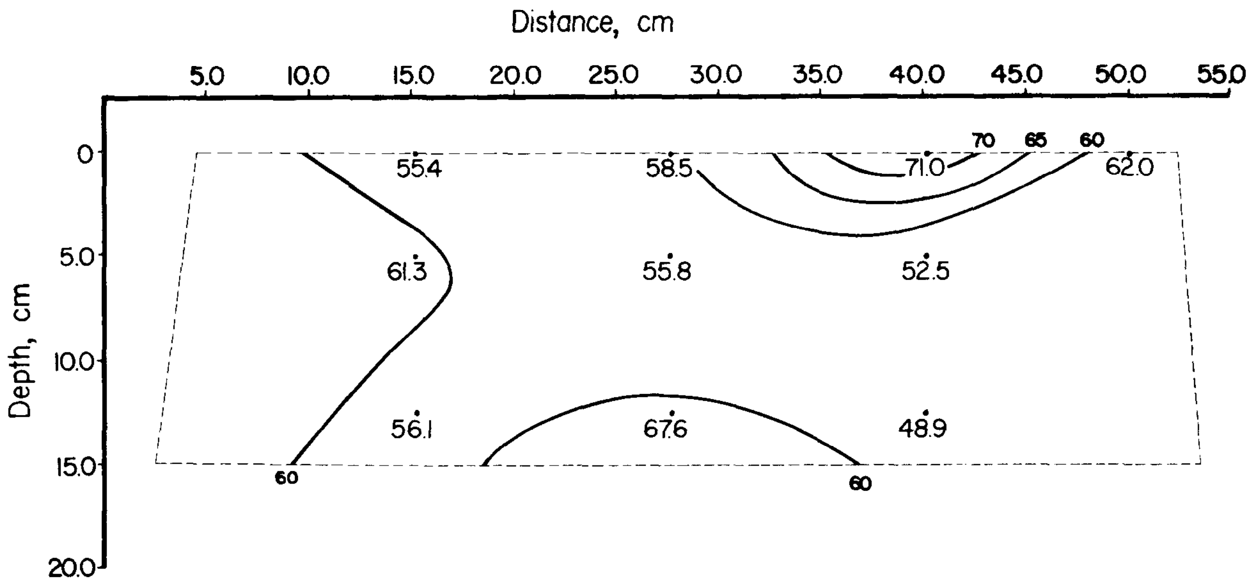

Figure 108. Distribution of the moisture content given in percent by weight for the initially dry Toledo dredged material from Experiment B dissected 151 hr after the application of water. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

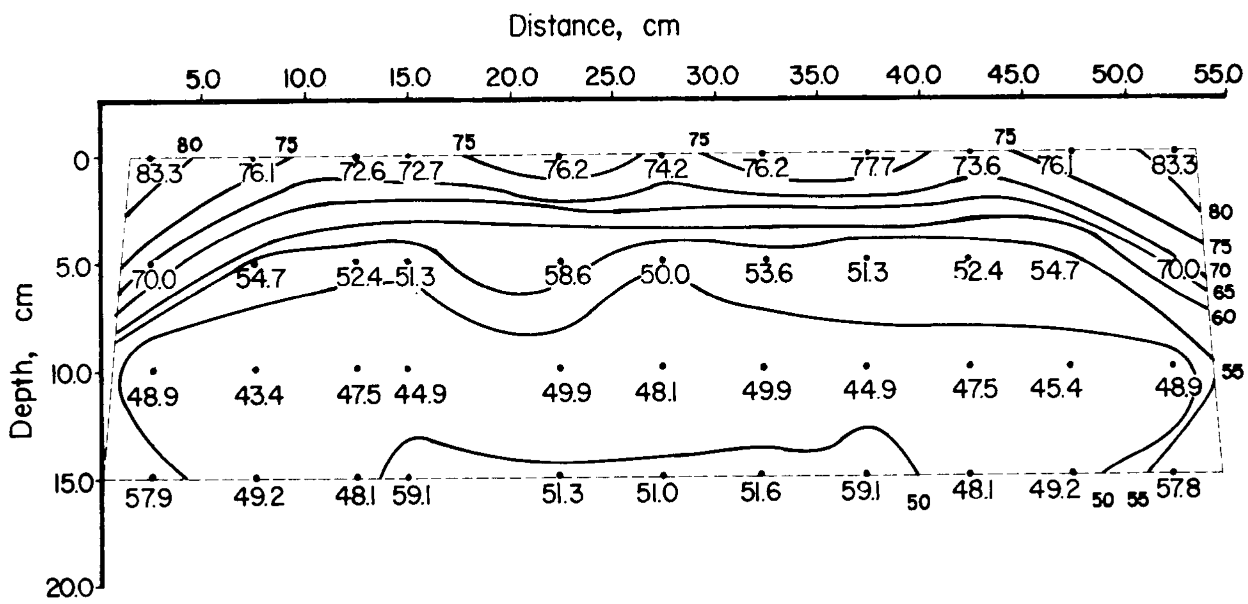

Figure 109. Distribution of the moisture content given in percent by weight for the initially dry Norfolk dredged material from Experiment B dissected 156 hr after the application of water. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

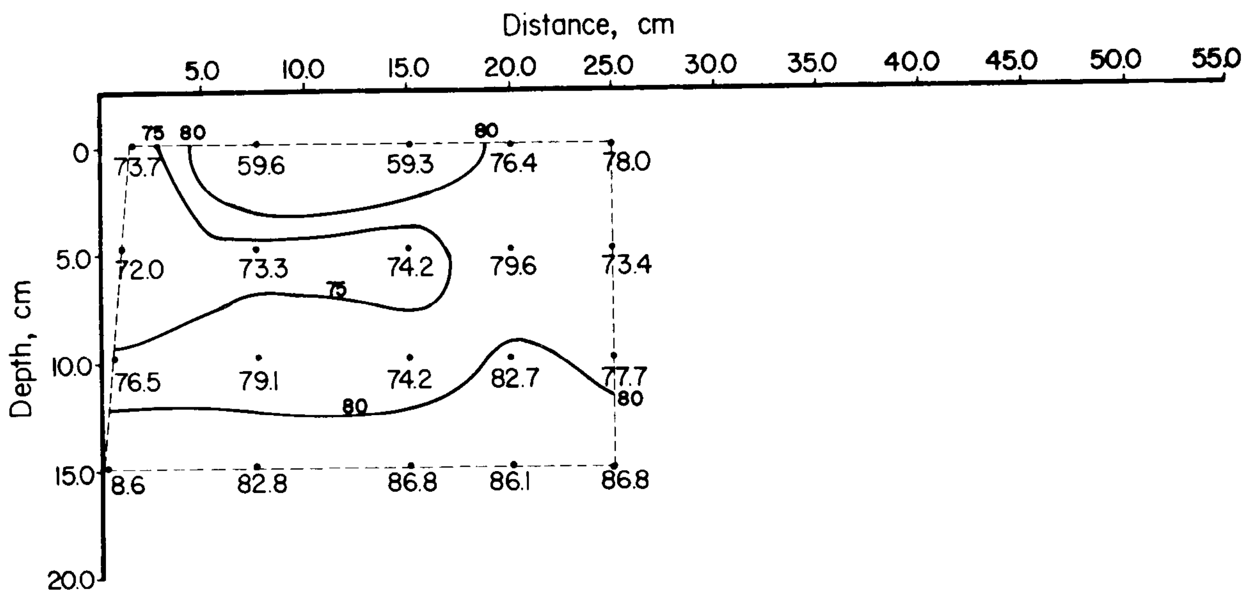

Figure 110. Distribution of the moisture content given in percent by weight for the initially wetter Philadelphia dredged material from Experiment B dissected 195 hr after the application of water. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

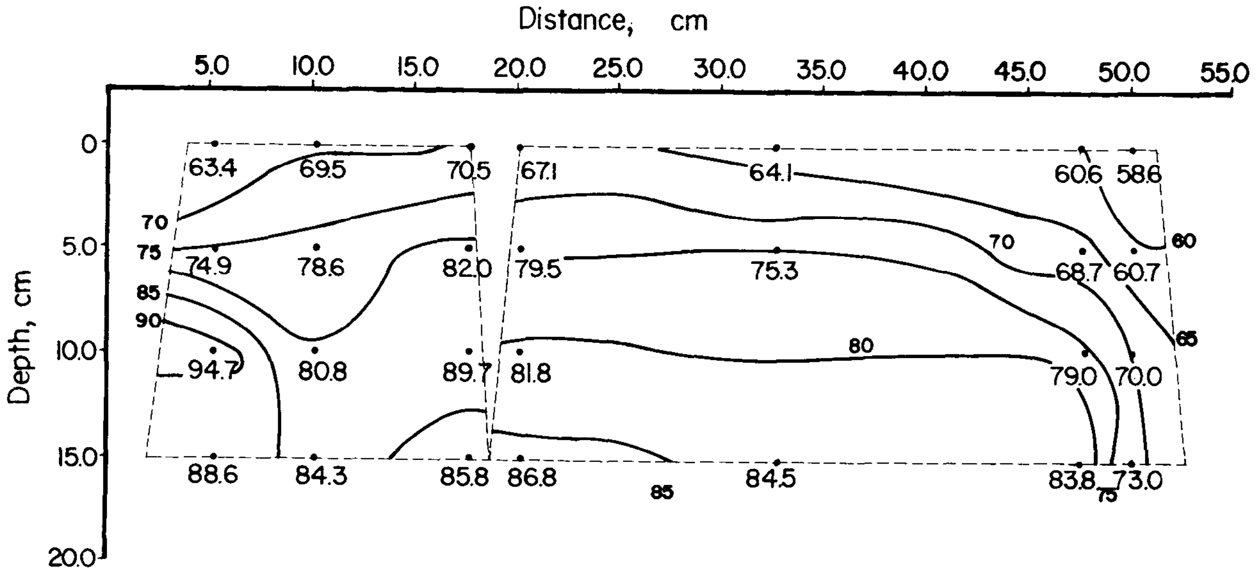

Figure 111. Distribution of the moisture content given in percent by weight for the initially wetter Toledo dredged material from Experiment B dissected 195 hr after the application of water. Depth was measured from the surface of the material and distance was measured from one edge of the container. The area enclosed by dashed lines represents the approximate cross section of the dried material

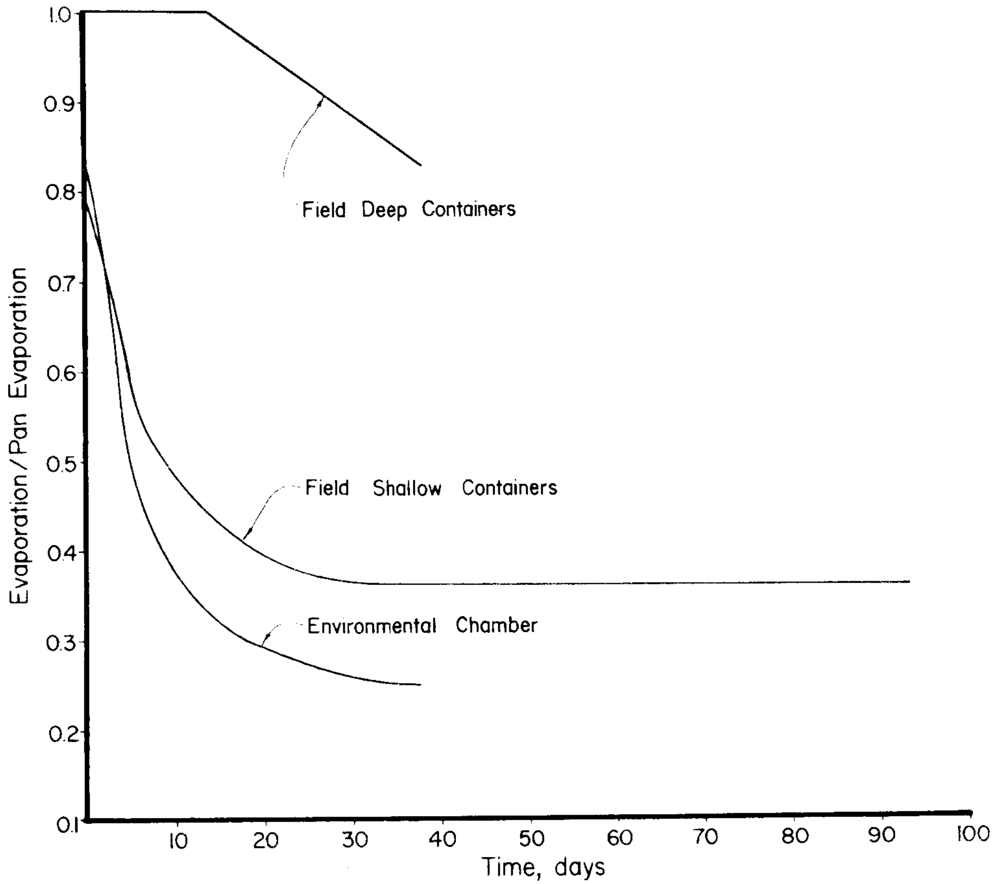

Figure 112. Comparison of evaporation data from different environments and with different thickness drying layers for the Mobile material. Evaporation is expressed as a fraction of the free-water evaporation

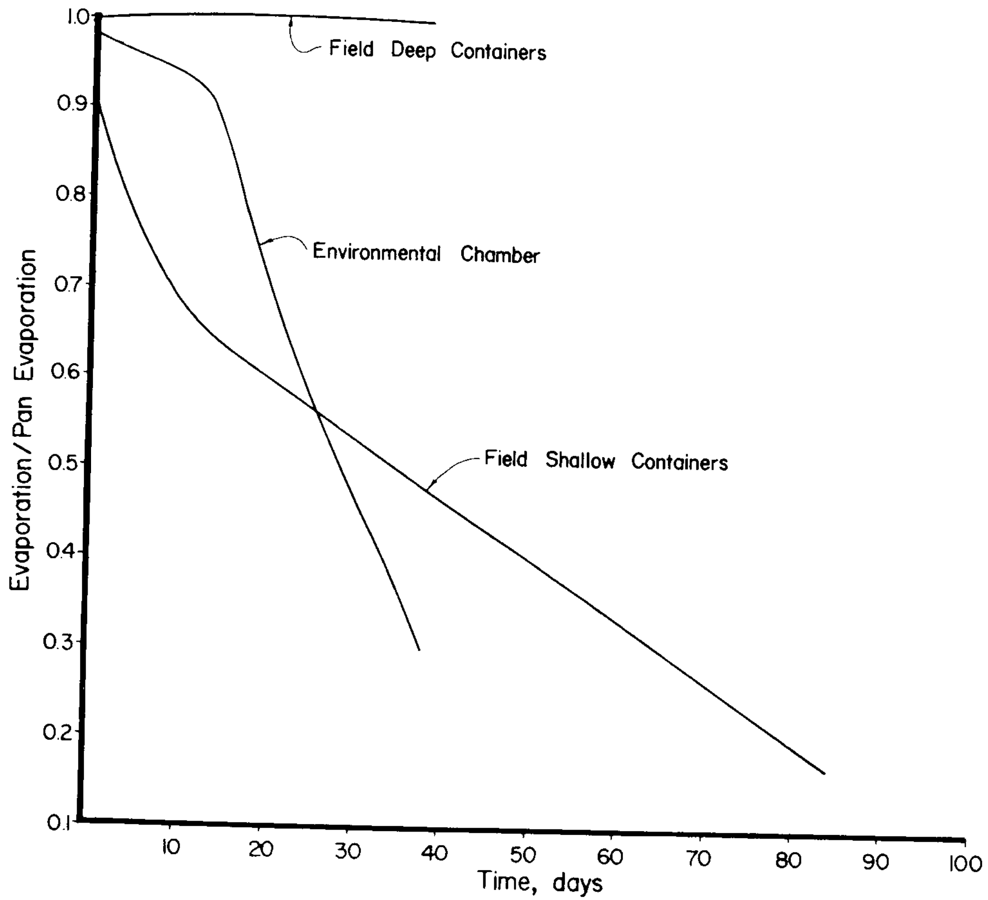

Figure 113. Comparision of evaporation data from different environments and with different thickness drying layers for the Philadelphia material. Evaporation is expressed as a fraction of the free-water evaporation

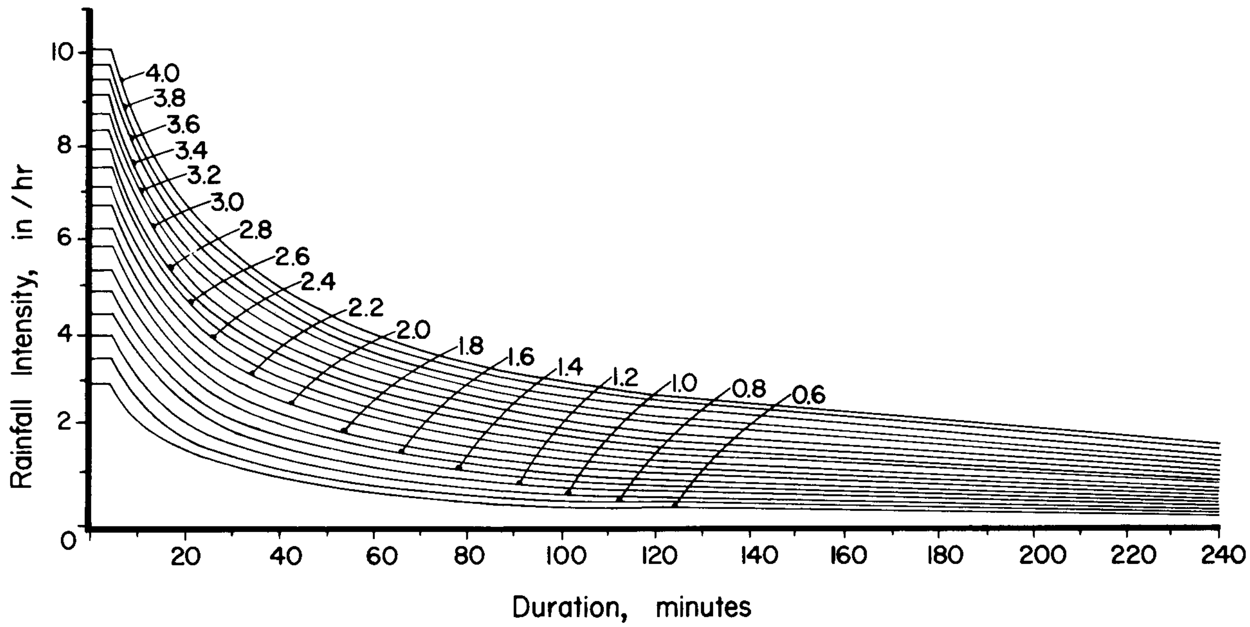

Figure 114. The rainfall intensity as a function of duration for storms of different sizes (after Hathaway, 1945). Conversion to metric can be acheived by multiplying the rates and the amounts per storm by 2.54 cm/in

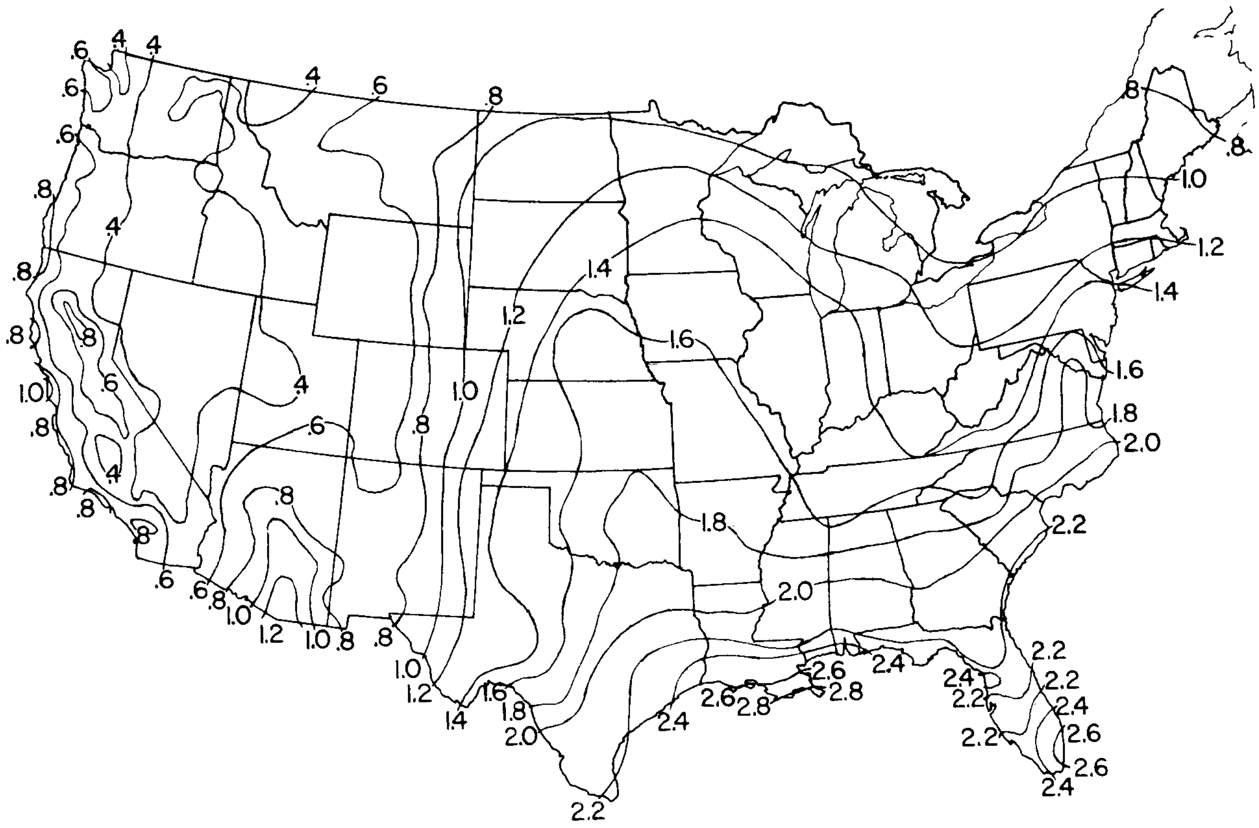

Figure 115. Two year, one hour rainfall in inches for the continental United States. Conversion to metric may be used by multiplying the rates by 2.54 cm/in (after Hathaway, 1945)

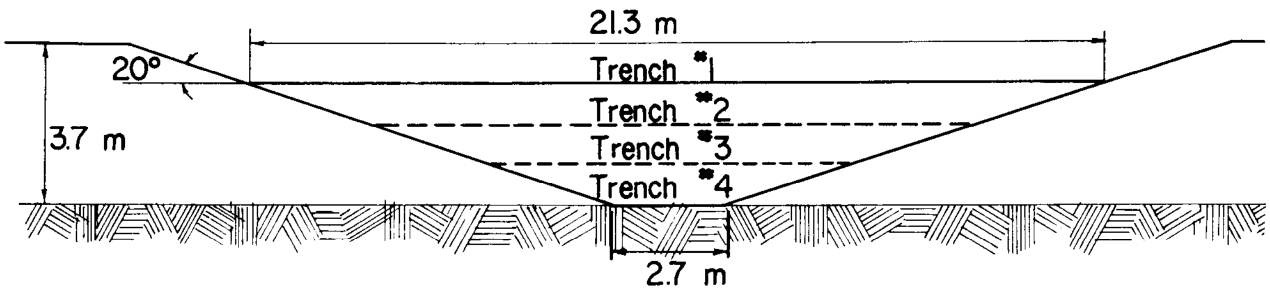

Figure 116. Excavation procedure

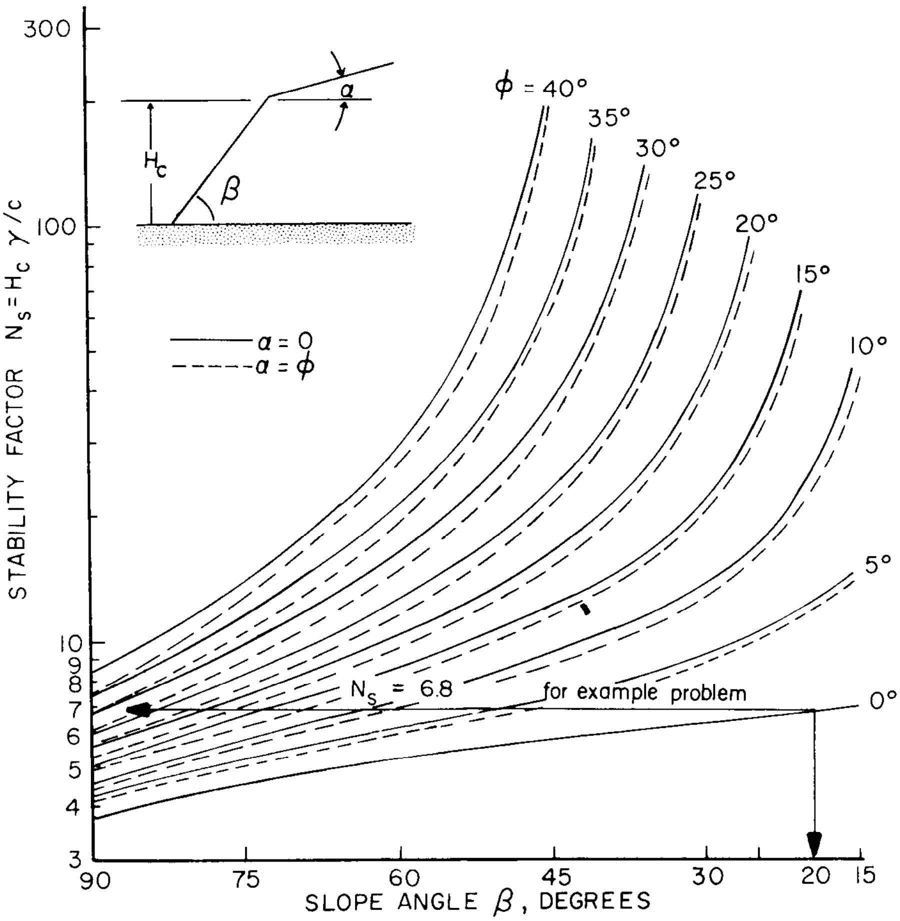

Figure 117. Effect of slope angle and friction angle on stability factor (from Winterkorn and Fang, 1975)

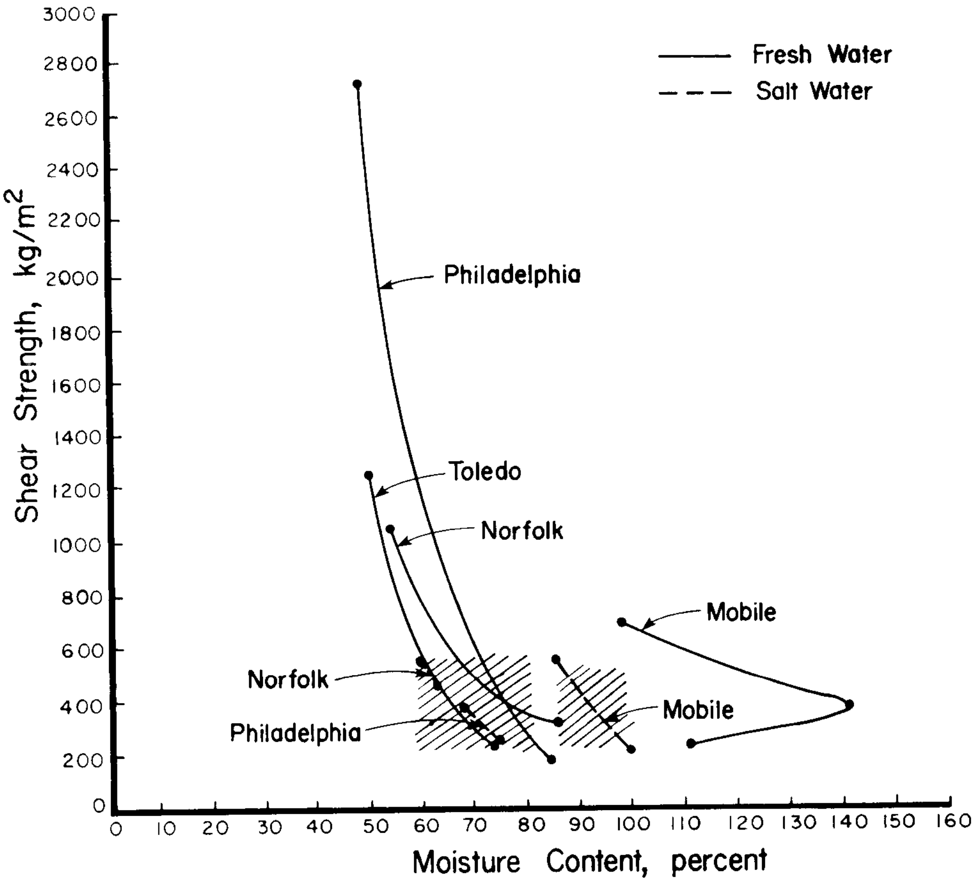

Figure 118. Shear strength of the dredged material as a function of moisture content. Some materials were prepared with saltwater while others were prepared with freshwater

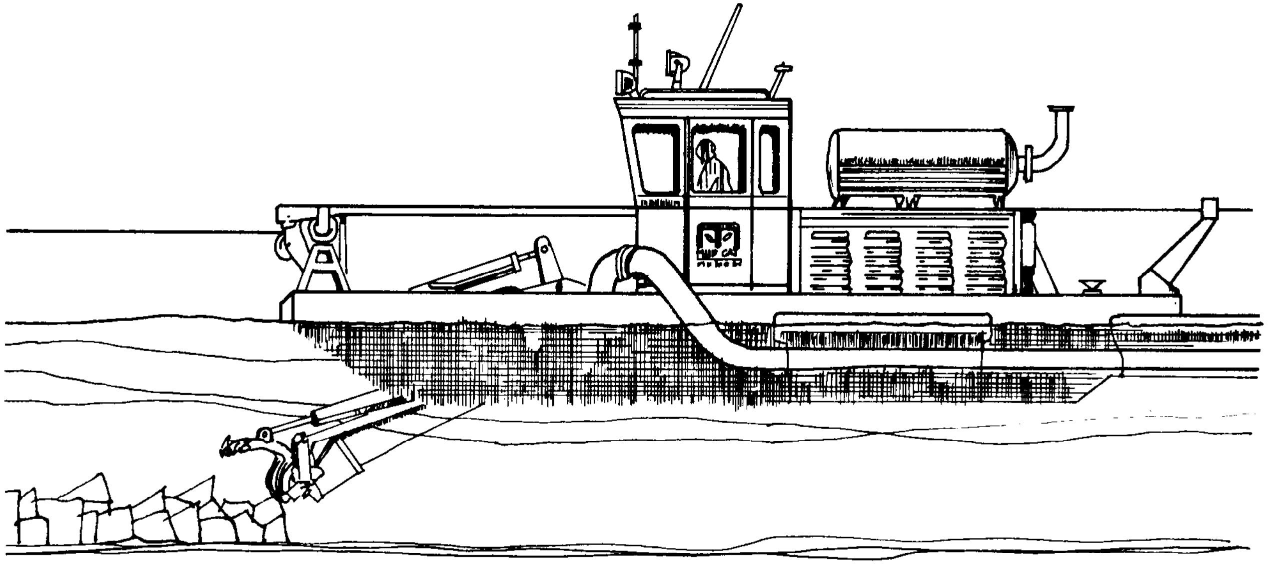

Figure 119. Schematic of small cable pulled dredge

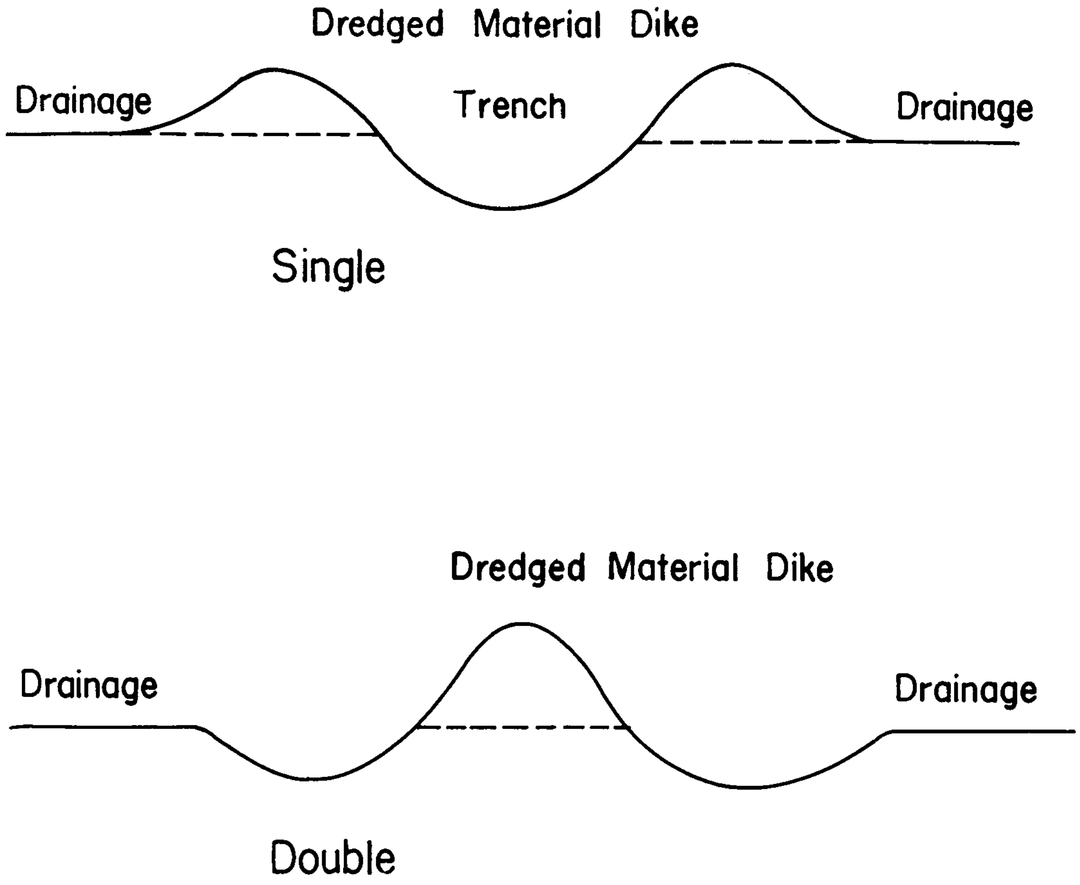

Figure 120. Single and double indentation trenches

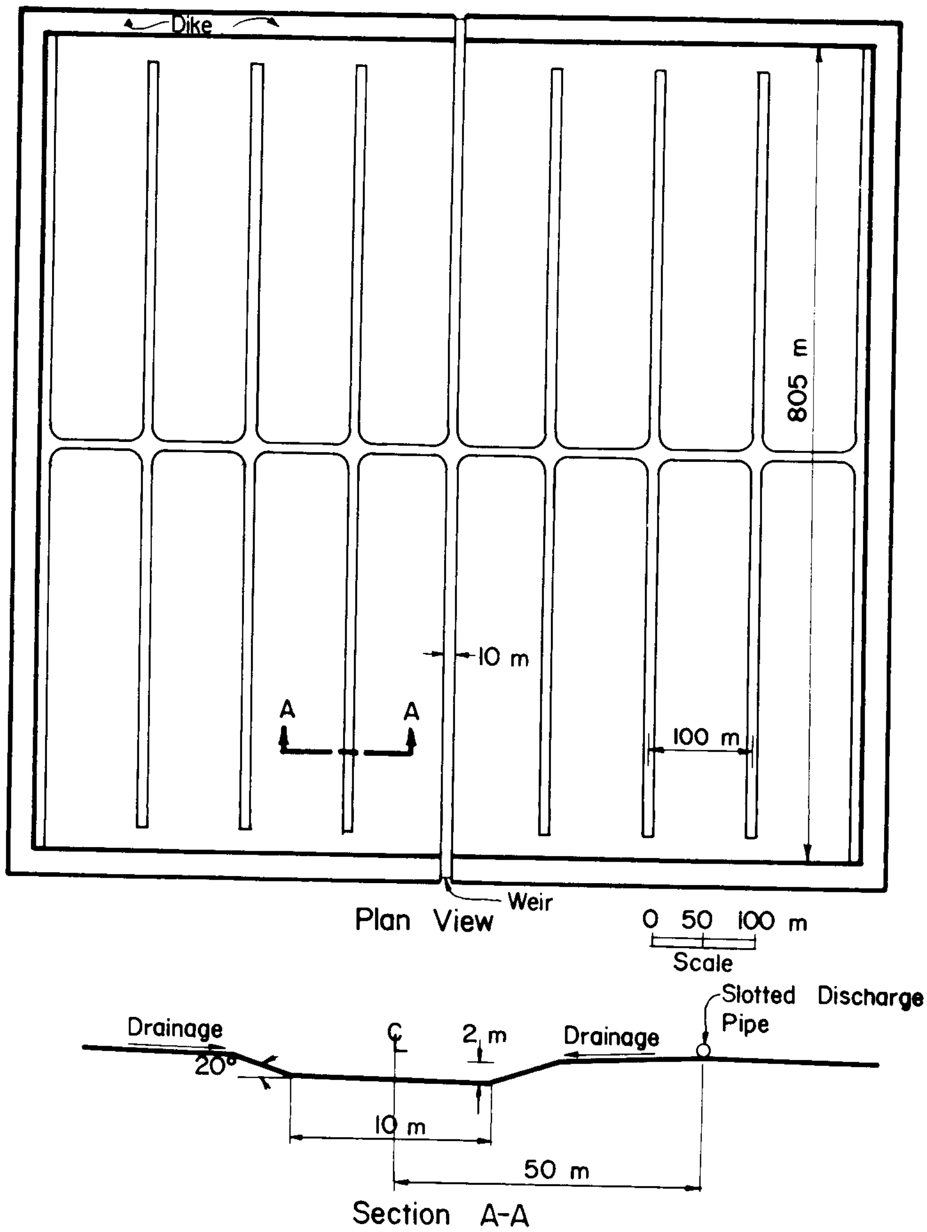

Figure 121. Example management procedure: trench drainage system

APPENDIX A: DREDGED MATERIAL SAMPLE FIELD REPORT

Philadelphia, Pennsylvania

Location: Confinement area on the New Jersey side of the river.

Date: 14 August 1975

Position within sample area: The material sampled had been scooped from adjacent to the outfall several days before sampling.

Age of deposit: Accumulated over a period of years.

Vegetation: Absent in area sampled. Phragmites had taken over large areas of the disposal site, however.

Original source of material: Dredged from existing channel in area immediately adjacent to and upstream of the location. The tide runs above the areas from which the material was dredged.

Water sample: Runoff taken from outfall.

Condition of material and the observations: The confinement area was originally a wet, low-lying field. The material had cracks 20 cm deep, 2 to 4 cm wide. The horizontal dimensions of the crust were 20 to 50 cm. Footing was unstable and water, perhaps from a rain which fell the previous night, was standing in the bottom of the cracks. Care was needed to place one foot at the center of each piece of crust and not to step on the same piece twice. Samples for moisture and density were taken at three depths. The material was black except for the very surface and the material adjacent to the cracks.

Toledo, Ohio

Location: Island #18

Date: 26 August 1975

Position within sample area: About 1000 m from inflow and 3 to 4 m from dike facing dredged channel.

Age of deposit: Unknown.

Vegetation: Dense cover of herbaceous vegetation.

Original source of material: Dredged from existing channel.

Water sample: Collected from surface water.

Condition of material and the observations: The deposition area was originally underwater. Recent heavy rains had not yet drained from the disposal area and the entire area was under water. The material had cracked before the rain and the cracks had not swelled shut even when submersed. Crust units with horizontal dimensions of 20 to 30 cm visible through the water. Footing was unstable and treacherous, especially when one stepped in the cracks. The material was black and of high moisture content. Free water drained from the sample containers when they were overfilled. Triplicate soil samples were taken for density and moisture content at field moisture. No penetrometer readings were taken due to very wet conditions. The deposit of dredged material was nearly level.

Norfolk, Virginia

Location: Craney Island

Date: 27 August 1975

Position within sample area: See location marked on Figure A1.

Age of deposit: 4 months.

Vegetation: Absent over large area. Phragmites were growing on the levees.

Original source of material: Dredged from existing channels.

Water sample: Taken as leachate water at a depth of 45 cm.

Condition of materials and the observations: The deposition area was originally part of the bay. The surface of the material was dry and cracked. Crusts were 15 to 30 cm thick and supported a man without difficulty except in wet drainage channels. By repeated jumping up and down on the crust, a block could be forced to a depth of about 50 cm. The crust was in units with vertical dimensions of 20 to 50 cm. The cracks were 20 to 60 cm deep and were as wide as 5 cm at the surface. Definite stratification of the material was observed. Thin sand layers were evident and efforts were made to avoid these when sampling. A layer of partially decomposed organic matter was also evident at 15 cm at some locations. The crust flaked off easily on the surface in units typically 0.5 to 1.5 cm thick. At greater depths, the cleavage planes were 3 to 5 cm apart. Some 1-cm-thick disks of crust 10 cm in diameter were observed. The bulk samples were taken below the crust and above sand layers. Cone penetrometer readings were taken at four locations and samples for moisture content and bulk density were collected at three depths at all but the wettest locations where only two samples were collected.

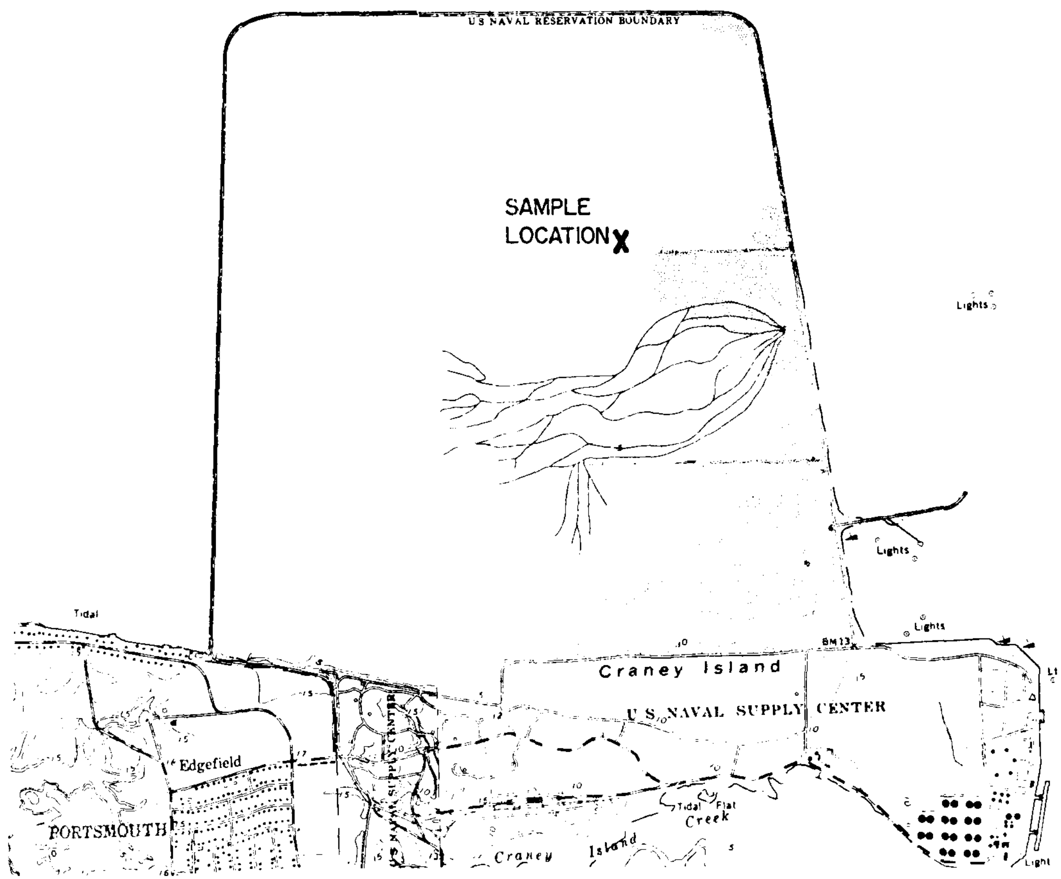

Figure A1. Craney Island dredged disposal area showing sample collection area

Mobile, Alabama

Location: Upper confinement area.

Date: 18 September 1975

Position within sample area: Samples were taken from the north side of the area, 15 m from the dike, adjacent to the barge tie-up.

Age of deposit: Last lift placed in 1973.

Vegetation: Sparse grass.

Original source of material: Dredged from existing channels in the adjacent river. Probably taken from below a saltwater wedge.

Water sample: Leachate collected from sample hole.

Condition of material and the observations: The disposal area was originally a low-lying marsh. The material was dried and cracked on the surface and no difficulty in mobility was encountered. The crust was broken into blocks with typical dimensions of 30 to 50 cm with channels 3 to 7 cm wide and 30 cm deep. The dried crust was removed from the surface and the samples were shoveled from the material below the crust. Water seeped into the hole at about 60 cm. The material collected was black and slippery.

APPENDIX B: MONTHLY METEOROLOGICAL RECORD

November 1975

		Air Temperature*		Relative Humidity*	
Day	Radiation cal/cm^2/day	Max C	Min C	Max %	Min %
1	312.3	27.8	12.8	100	35
2	208.2	30.6	13.9	100	65
3	268.9	26.7	14.4	100	36
4	268.9	22.8	11.1	100	45
5	221.2	25.6	8.9	100	36
6	316.6	27.2	9.4	100	37
7	333.9	28.9	12.8	100	47
8	329.6	28.3	17.2	100	47
9	355.6	29.4	17.8	100	42
10	277.6	23.3	7.2	100	24
11	373.0	27.2	3.3	100	34
12	286.2	17.8	2.2	30	12
13	273.2	15.0	0.0	82	18
14	255.9	20.0	0.0	100	16
15	277.6	23.3	1.7	100	36
16	238.5	25.0	10.0	100	40
17	346.3	25.6	13.3	100	40
18	247.2	23.9	12.8	100	60
19	186.5	26.1	17.2	100	50
20	203.8	11.7	0.6	82	30
21	225.5	11.1	0.0	95	25
22	208.2	10.0	0.0	66	30
23	216.9	13.9	0.0	100	17
24	186.5	14.4	0.0	100	28
25	225.5	17.8	0.0	100	34
26	190.8	6.7	0.0	100	22
27	203.8	15.0	0.0	100	30
28	169.1	27.2	10.0	100	48
29	125.8	25.6	20.6	100	60
30	143.1	22.8	0.0	100	22

*Max = daily maximum; Min = daily minimum.

December 1975

Day	Radiation Cal/cm^2/day	Air Temperature* Max C	Air Temperature* Min C	Relative Humidity* Max %	Relative Humidity* Min %
1	125.8	12.8	0.0	100	18
2	299.3	19.4	0.0	100	18
3	329.6	22.2	0.0	100	37
4	143.1	23.3	10.0	93	68
5	134.4	24.4	16.7	100	57
6	368.6	18.9	7.2	100	48
7	108.4	10.6	15.6	74	69
8	216.9	17.8	0.6	100	40
9	160.5	18.3	2.2	100	24
10	190.8	23.9	5.6	80	27
11	216.9	25.0	10.6	100	39
12	212.5	24.4	13.3	100	52
13	138.8	23.3	17.2	100	58
14	173.5	26.7	2.2	100	42
15	56.4	3.3	2.2	100	77
16	21.7	8.3	1.1	100	54
17	125.8	13.3	0.0	100	40
18	173.5	2.8	0.0	65	33
19	121.4	6.1	0.0	100	27
20	130.1	15.6	0.0	100	29
21	169.1	11.7	0.0	100	30
22	121.4	11.1	2.2	95	40
23	151.8	15.0	0.0	100	46
24	21.7	7.8	4.4	100	100
25	17.3	6.1	1.1	99	70
26	143.1	14.4	0.0	100	30
27	199.5	18.9	0.0	100	28
28	182.2	21.1	5.6	100	60
29	78.1	3.3	0.0	98	54
30	112.8	8.9	0.0	96	34
31	39.0	18.9	0.0	96	16

*Max = daily maximum; Min = daily minimum

January 1976

		Air Temperature*		Relative Humidity*	
	Radiation	Max	Min	Max	Min
Day	$cal/cm^2/day$	C	C	%	%
1	56.4	23.9	7.2	100	56
2	17.3	16.7	2.2	100	36
3	260.2	6.1	0.0	46	25
4	169.1	7.2	0.0	94	18
5	56.4	4.4	0.6	64	38
6	47.7	17.8	0.6	100	72
7	255.9	12.8	0.0	100	34
8	112.8	2.2	0.0	48	22
9	173.5	12.8	0.0	93	38
10	99.8	19.4	2.2	100	48
11	273.2	17.8	2.2	100	38
12	199.5	22.8	0.0	100	46
13	8.7	25.6	0.0	95	38
14	117.1	14.4	10.0	87	30
15	117.1	17.8	0.0	100	20
16	182.2	17.8	0.0	100	15
17	112.8	17.2	0.0	93	21
18	177.8	21.1	0.0	100	30
19	182.2	21.7	7.8	100	45
20	160.5	11.1	0.0	100	40
21	143.1	16.7	0.0	100	20
22	186.5	19.4	0.0	100	22
23	160.5	22.2	1.1	100	44
24	99.8	18.3	14.4	100	86
25	186.5	20.0	2.2	100	37
26	169.1	6.1	0.0	100	50
27	147.5	10.0	0.0	100	26
28	203.8	14.4	0.0	100	18
29	277.6	21.1	0.0	100	16
30	260.2	22.2	0.0	100	30
31	143.1	12.2	0.0	100	36

*Max = daily maximum; Min= daily minimum

February 1976

Day	Radiation $cal/cm^2/day$	Air Temperature* Max C	Air Temperature* Min C	Relative Humidity* Max %	Relative Humidity* Min %
1	290.6	20.0	0.0	90	18
2	229.9	25.6	1.7	93	17
3	294.9	25.0	0.0	90	49
4	130.1	24.4	8.3	100	64
5	47.7	17.8	3.9	100	95
6	143.1	5.6	0.0	90	51
7	229.9	6.7	0.0	62	30
8	281.9	20.0	3.9	96	38
9	299.3	24.4	17.8	100	63
10	130.1	25.0	17.8	88	61
11	151.8	26.1	13.9	96	56
12	186.5	23.3	13.3	100	54
13	294.9	25.0	13.3	100	52
14	164.8	24.4	13.3	100	58
15	425.0	25.6	13.3	100	50
16	173.5	23.3	17.2	100	88
17	117.1	22.8	15.6	98	96
18	347.0	21.7	6.7	69	27
19	403.3	27.2	3.9	100	34
20	195.2	23.3	12.8	100	77
21	177.8	13.9	14.4	65	48
22	329.6	12.2	0.0	76	34
23	286.2	22.2	0.0	100	16
24	299.3	22.2	0.6	100	31
25	203.8	19.4	6.7	100	57
26	342.6	23.3	5.0	100	40
27	264.3	23.3	9.4	100	44
28	390.3	24.4	7.8	100	37
29	268.9	26.7	14.4	100	50

*Max = daily maximum; Min= daily minimum

March 1976

Day	Radiation $cal/cm^2/day$	Air Temperature* Max C	Air Temperature* Min C	Relative Humidity* Max %	Relative Humidity* Min %
1	268.9	26.7	16.7	100	57
2	416.4	27.8	18.3	100	57
3	95.4	27.2	18.9	100	76
4	360.0	27.8	17.3	94	67
5	203.8	17.2	4.4	94	93
6	47.7	8.9	5.0	100	100
7	86.7	15.6	8.3	100	100
8	56.4	13.3	6.1	100	72
9	368.6	13.3	2.8	100	74
10	108.4	20.0	1.1	100	66
11	151.8	20.6	11.1	100	92
12	355.6	25.0	8.3	100	31
13	151.8	8.3	3.9	55	100
14	173.5	8.9	3.9	100	100
15	130.1	16.1	8.3	100	91
16	468.4	13.9	0.0	76	27
17	451.0	16.7	0.0	100	27
18	377.3	23.3	4.4	100	57
19	407.2	26.7	11.1	100	75
20	394.2	27.8	10.6	96	19
21	420.3	22.2	3.3	82	14
22	130.1	23.3	5.0	84	33
23	212.1	23.3	4.4	100	35
24	260.2	21.7	11.1	100	100
25	260.2	28.3	17.8	100	70
26	204.9	27.2	13.3	100	64
27	91.1	22.2	4.4	100	23
28	173.0	22.2	9.4	92	87
29	295.0	20.8	18.3	100	58
30	169.1	19.4	3.9	70	61
31	494.4	18.9	1.7	100	28

*Max = daily maximum; Min = daily minimum

April 1976

Day	Radiation cal/cm^2/day	Air Temperature* Max C	Air Temperature* Min C	Relative Humidity* Max %	Relative Humidity* Min %
1	464.1	24.4	3.3	100	19
2	221.2	25.0	5.6	100	32
3	102.1	23.3	8.9	100	63
4	0.0	21.2	12.8	100	97
5	121.0	22.2	12.3	100	100
6	412.1	23.3	11.7	100	50
7	143.1	18.3	11.7	100	94
8	485.3	23.3	11.1	100	42
9	503.1	24.4	11.7	82	35
10	217.0	25.0	11.7	98	44
11	416.4	26.1	14.4	100	42
12	273.2	25.9	13.3	100	56
13	360.0	25.6	17.8	100	84
14	203.9	25.6	17.8	100	67
15	55.9	25.6	11.1	100	63
16	338.3	23.3	11.1	100	90
17	190.9	24.4	19.4	95	87
18	190.9	20.6	13.3	100	100
19	312.3	24.4	18.9	100	80
20	338.3	25.6	13.3	100	41
21	468.4	25.6	8.9	100	35
22	572.5	27.8	13.3	100	58
23	242.9	24.4	18.9	100	73
24	394.2	29.4	17.2	100	75
25	533.5	26.1	11.1	100	28
26	529.2	25.6	11.1	100	44
27	399.0	26.7	13.3	100	48
28	234.2	26.1	17.2	100	65
29	91.1	21.1	12.2	100	100
30	70.1	17.2	11.1	100	90

*Max = daily maximum; Min = daily minimum

May 1976

Day	Radiation cal/cm^2/day	Air Temperature* Max C	Min C	Relative Humidity* Max %	Min %
1	334.0	21.1	11.1	100	40
2	576.4	26.7	6.7	100	23
3	529.2	28.3	10.0	97	26
4	503.1	26.7	12.2	100	36
5	368.2	25.6	14.4	100	56
6	416.1	31.1	18.9	100	42
7	95.0	21.1	13.3	95	91
8	312.3	19.4	13.3	100	75
9	416.4	21.1	14.4	97	100

*Max = daily maximum; Min = daily minimum

APPENDIX C: DRAINAGE PROGRAM

1. Integration of:

$$\frac{-3W}{A} t + c = \int \frac{2zdz}{b^3 + z^3} = \int \frac{2zdz}{(b + z)(b^2 - bz + z^2)}$$

$$= + 2 \int \frac{Adz}{b + z} + 2 \int \frac{(Bz + C)dz}{b^2 - bz + z^2}$$

Solving for A and Bz + C gives:

$$\left(Ab^2 - Abz + Az^2 \right) + Bbz + Cb + Bz^2 + Cz = z$$

or:

$$Ab^2 + 0 + Cb = 0$$

$$-Ab + Bb + C = 1$$

$$A + B = 0.$$

When this system of equations is solved, it can be seen that:

$$A = \frac{-1}{3b}$$

$$B = + \frac{1}{3b}$$

and

$$C = 1/3$$

Now the right hand side of the equation is:

$$= -2 \int \frac{\left(\frac{1}{3b}\right)dz}{b + z} + 2 \int \frac{\left(\frac{1}{3b}\right)z + 1/3}{b^2 - bz + z^2} dz.$$

This can be rewritten as:

$$= \frac{-2}{3b} \int \frac{dz}{b + z} + \frac{2}{3b} \int \left(\frac{z + b}{b^2 - bz + z^2} \right) dz.$$

2. The first term on the right hand side of the equation is in an integrable form; operating on the second term yields:

$$= \frac{-2}{3b} \int \frac{dz}{b + z} + \frac{1}{3b} \int \frac{(2z - b)dz}{b^2 - bz + z^2} + \int \frac{dz}{b^2 - bz + z^2} .$$

The second term is also in an integrable form; operating on the third term on the right yields:

$$= \frac{-2}{3b} \int \frac{dz}{b + z} + \frac{1}{3b} \int \frac{(2z - b)dz}{b^2 - bz + z^2} + \int \frac{dz}{\frac{b^2}{4} - bz + z^2 + \frac{3}{4} b^2}$$

or:

$$= + \frac{2}{3b} \left(-\ln(b + z) + 1/2 \ln(b^2 - bz + z^2) \right) + \frac{dz}{(z - \frac{b}{2})^2 + 2\left(\sqrt{\frac{3}{2}}\right)b} + D.$$

This last term is now in standard form to give:

$$= + \frac{2}{3b} \left(-\ln(b + z) + 1/2 \ln(b^2 - bz + z^2) \right) + \frac{2}{\sqrt{3}\, b} \arctan \frac{2\left(z - \frac{b}{2}\right)}{\sqrt{3}\, b} + D$$

or finally where D is the integration constant:

$$\frac{-3w}{A} t = \frac{2}{3b} \left[-\ln(b + z) + 1/2 \ln(b^2 - bz + z^2) + \sqrt{3} \arctan \frac{2\left(z - \frac{b}{2}\right)}{\sqrt{3}\, b} + D. \right]$$

```
      C
      C   SOLUTION TO RUNOFF-TIME PROBLEM CONSIDERING SPOIL SITES OF VARYING AREA AND
      C   WEIR LENGTH WITH VARYING DURATIONS OF RAINFALL RATES AND WATER BUILDUP.
      C
      C
      C     AI = RAINFALL IN INCHES
      C     AJ = DURATION OF RAINFALL IN HOURS
      C     AR = RATE OF RAINFALL IN INCHES PER HOUR
      C      R = RATE OF RAINFALL IN FEET PER SECOND
      C      K = AREA OF SPOIL SITE IN ACRES
      C   AREA = AREA OF SPOIL SITE IN SQUARE FEET
      C   WEIR = LENGTH OF WEIR IN FEET
      C     HT = HEIGHT OF WATER OVER SPOIL SITE
      C     TF = FILLING TIME IN SECONDS
      C    TFH = FILLING TIME IN HOURS
      C     TR = RUNOFF TIME IN SECONDS
      C    TRH = RUNOFF TIME IN HOURS
      C     TH = RUNOFF TIME IN HOURS
      C      T = TOTAL TIME: TFH + TRH
      C    CON = CONSTANT FOR CALCULATING TOTAL TIME FROM CURVES
      C
      C
0001        WRITE(6,100)
0002  100 FORMAT('1',/,4X,'SITE AREA',3X,'WEIR LENGTH',3X,'RAINFALL RATE',3X
         1,'WATER HEIGHT',7X,'TIME DURATION OF',8X,'CORRELATION',/,61X,'FILL
         2ING',3X,'RUNOFF',3X,'TOTAL',4X,'CONSTANT FOR',/,6X,'ACRES',8X,'FEE
         3T',8X,'INCHES/HOUR',8X,'INCHES',8X,'HOURS',5X,'HOURS',3X,'HOURS',5
         4X,'TOTAL TIME',//)
0003        CALL ONE
0004        CALL TWO
0005        STOP
0006        END
```

```
      SLBRCLTINE CNE
      DO 10 K=5C,200,5C
      AREA=K*4356C
      DC 10 L=25,10C,25
      WEIR=L
      DC 10 J=1,12
      AR=FLCAT(J)/4.
      R=AR/(12.*3600.)
      DO 10 M=2,10,2
      AM=M
      HT=FLOAT(M)/12.
      Z=HT**.5
      X=(3.*WEIR*HT**1.5)/AREA
      Y=(3.*WEIR)/(R*AREA)
      IF(R.LT.X)GCTC10
      TF=-.3205*AREA**(2./3.)/(R**(1./3.)*WEIR**(2./3.))*(ALOG(1.-Y**(1.
     1/3.)*Z)-.5*ALOG(1.+Y**(1./3.)*Z+Z**2.*Y**(2./3.))-1.732*(ATAN(-1.1
     547*Z*Y**(1./3.)-.57735)-ATAN(-.57735)))
      TFH=TF/360C.
      TR=Z*2.*AREA/(3.*WEIR)
      TRH=TR/360C.
      T=TFH+TRH
      CON=.00005349*AREA/WEIR
      WRITE(6,200)K,L,AR,AM,TFH,TRH,T,CON
  200 FORMAT(7X,I3,9X,I3,12X,F4.2,11X,F5.2,7X,F6.2,4X,F6.2,3X,F6.2,5X,F6
     *.3)
   10 CONTINUE
      RETURN
      END
```

```
      SUEROUTINE TWO
      DC 10 K=5C,200,50
      AREA=K*4356C
      CO 10 L=25,100,25
      WEIR=L
      DO 10 J=1,12
      AR=FLCAT(J)/4.
      R=AR/(12.*3600.)
      CO 10 N=1,10
      AM=FLCAT(N)/5.
      HT=AM/12.
      Z=HT**.5
      X=(3.*WEIR*HT**1.5)/AREA
      Y=(3.*WEIR)/(R*AREA)
      IF(R.LT.X)GCTO10
      TF=-.3205*AREA**(2./3.)/(R**(1./3.)*WEIR**(2./3.))*(ALOG(1.-Y**(1.
     1/3.)*Z)-.5*ALOG(1.+Y**(1./3.)*Z+Z**2.*Y**(2./3.))-1.732*(ATAN(-1.1
     547*Z*Y**(1./3.)-.57735)-ATAN(-.57735)))
      TFH=TF/3600.
      TR=Z*2.*AREA/(3.*WEIR)
      TRH=TR/36C0.
      T=TFH+TRH
      CON=.00005349*AREA/WEIR
      WRITE(6,200)K,L,AR,AM,TFH,TRH,T,CON
  200 FORMAT(7X,I3,9X,I3,12X,F4.2,11X,F5.2,7X,F6.2,4X,F6.2,3X,F6.2,5X,F6
     *.3)
   10 CONTINUE
      RETURN
      END
```

```
      A=50.0*43560.0*0.3048*0.3048
      SIGMA=2.0
      W=25.0*0.3048
      DO 10 I=1,8
      R=0.2*0.0254
      DO 15 J=1,14
      IF(J.EQ.11) R=0.0762
      IF(J.EQ.12) R=0.101
      IF(J.EQ.13) R=0.127
      IF(J.EQ.14) R=0.152
      B=-((R*A)/(2.05*W))**0.333
      H=0.1*0.0254
   25 CONTINUE
      Z=SQRT(H)
      CALL TVAL (B,R,Z,T1)
      T2=((2.0*A)/2.05*W) /SQRT(H)

      T2=T2/60.0
      TT=T1+T2
      WRITE (6,20) A,SIGMA,W,R,H,T1,T2,TT
      H=H+0.1*0.0254
      IF (H.LE.0.1372) GO TO 25
      R=R+0.2*0.0254
   15 CONTINUE
      W=W+25.0*0.3048
   10 CONTINUE
   20 FORMAT(8F16.5)
      STOP
      END
```

```
      SUBROUTINE TVAL(B,R,Z,T1)
      FACTOR=-2.0*(B**2)/(2.05*R)
      FIRST=ALOG((B+Z)/B)
      SECOND=0.5*ALOG((B**2-B*Z+Z**2)/B**2)
      THIRD=SQRT(3.0)* ATAN(2.0*(Z-0.5*B)/(SQRT(3.0)*B))
      FOURTH=SQRT(3.0)*ATAN(-1.0/SQRT(3.0))
      T1=FACTOR*(FIRST-SECOND-THIRD+FOURTH)
      T1=T1*60.0
      RETURN
      END

C
C *************************************************************
C      ***************************************
C
C
      DO 15 I=1,1000,1
      R=49.38/(I+10.0)**0.7516
      PRINT, R,I
           $

   15 CONTINUE
      STOP
      END


C
C
01) IFY032I NULL PROGRAM

*STATISTICS* 002 DIAGNOSTICS THIS STEP
```

APPENDIX D: SPECIAL EQUIPMENT

Information on Mud Cat Model MC-15

Manufacturer: National Car Rental
5555 West Loop South, Suite 555
Houston (Bellaire), Texas 77401

Weight: 8981 kg dry

Length: 11.8 m

Width : 2.4 m

Height: 2.8 m overall

Draft : 0.5 m

Floating Clearance: 2.0 m with lights removed

Single Cutting Depth: 2.4 x 0.5 m maximum depth

Operating Range: to 4.6 m maximum depth

Material Removal: to 91.7 m^3/hr

Traverse Speed: 15.2 m/min maximum forward and reverse

Average Cutting Speed: 2.4 to 3.6 m/min

Fuel Capacity: 1521.6 l

Fuel Consumption Rate: 27.5 l/hr

Cost: $88,850.00

Total Hourly Owning Cost: $13.93

Total Hourly Operating Cost: $23.17

Total Hourly Costs: $37.10

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Brown, K W
Feasibility study of general crust management as a technique for increasing capacity of dredged material containment areas / by K. W. Brown, L. J. Thompson, Texas A & M Research Foundation, Texas A & M University, College Station, Texas. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1977.
79, [152] p. ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; D-77-17)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACW39-75-C-0120, (DMRP Work Unit No. 5A06)
Literature cited: p. 76-79.

1. Crusts. 2. Desiccation. 3. Disposal areas. 4. Dredged material. 5. Dredged material disposal. 6. Dredges.

(Continued on next card)

Brown, K W
Feasibility study of general crust management as a technique ... 1977. (Card 2)

I. Thompson, Louis Jean, joint author. II. Texas. A & M University, College Station. Research Foundation. III. United States. Army. Corps of Engineers. IV. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; D-77-17.
TA7.W34 no.D-77-17